Final Report, CAL/ARB Project 4-011

"EMISSION FACTORS FROM BURNING AGRICULTURAL WASTES COLLECTED IN CALIFORNIA"

Ellis F. Darley
Principal Investigator

Statewide Air Pollution Research Center
University of California, Riverside

January 1977

ABSTRACT

This project was initiated to determine the pollutant emission factors from burning 31 field, vine, and orchard crops and weeds in an out-of-doors, instrumented burning tower. The pollutants of concern were particulates, carbon monoxide and hydrocarbons. Size distribution of smoke particles was also determined. Field crops and weeds were burned as head and back fires at an air dry moisture level. Orchard and vine crops were burned in piles at two moisture levels and two systems of ignition in which the second pile of a pair was rolled on the embers of the first fire. As a class, field crops and weeds produced considerably more of all three pollutants than did orchard and vine crops. Back firing field crops resulted in lower emissions of particulates when compared with head firing but this was not so for carbon monoxide or hydrocarbons. There was no additional significant reduction of particulate or carbon monoxide obtained by drying most orchard crops below about 35 percent moisture (dry weight basis); there was a further reduction of hydrocarbon but the change was quite small. Rolling orchard fuel on to existing fires significantly increased emissions in most cases, but again the changes were relatively small. Most particles from all fires were submicron in size. Back firing produced significantly smaller particles than did head firing. Additionally drying orchard fuels had no real effect on particle size but the roll-on orchard fires produced significantly larger particles than the first fire of the pair.

This report was submitted in fulfillment of ARB Project No. 4-011 by the University of California at Riverside under partial sponsorship of the California Air Resources Board. Work was completed as of January, 1977

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ACKNOWLEDGEMENTS

The successful conduct of this project required considerable cooperation from the staff of the California Air Resources Board, which we gratefully acknowledge. Sydney Thornton first suggested that such a project be undertaken. She supervised preliminary studies and did the basic work of planning the selection, collection, and delivery to Riverside of the crops to be burned. We thank James Morgester for encouragement and valuable suggestions in organizing the study. Further, we appreciate the assistance given us by Beverly Daniels, Cheryl Haden, Davis Frisk, Roy Jackson, and Robert Leonard.

At the University of California, Riverside, Ervin Mateer supervised the operation of the burning tower and preparation of the fuels; his valuable assistance is acknowledged. Technical assistance during burning operations and treatment of data was provided by Brian Bellantuoni, David Clarke, Mark Fukuhara, and Hedy Zikratch. We want to especially recognize Dr. Shimshon Lerman, who assisted in technical operation and calibration of the cascade impactor used for particle size determination, and Minn Poe for her supervision of the data acquisition system, computer programing, and analysis of the data.

CONCLUSIONS

When emission factors for particulate, carbon monoxide, and hydrocarbon are compared for all fires of field crops and weeds versus all fires of orchard and vine crops, the former group consistently had higher factors for all three pollutants. For field crops the factors average about 18, 114, and 17 pounds of pollutant respectively, per ton of fuel burned and about 7, 56, and 9 pounds, respectively, for orchard crops. The low values from orchard fuels were achieved even though their moisture content on a dry weight basis was considerably higher than that in field fuels (about 32 and 12 percent, respectively). Thus it is reasonable to conclude that fine herbaceous fuels have higher emission factors than more coarse woody fuels.

Back firing field crops results in lower emissions of particulate than when head firing is used. There is little or no difference in emissions of carbon monoxide or hydrocarbons between the two methods. These results agreed with those of an earlier study on the burning of rice straw.

Once orchard crops are dried down to about 35 percent moisture on a dry weight basis, no additional benefit is realized in reducing particulate or carbon monoxide by drying the wastes on down to about 25 percent moisture. This is true whether the cold start type of ignition or the roll-on ignition is used. However, the additional drying does reduce hydrocarbons significantly with both cold and roll-on ignition although the absolute value changes are quite small. Within a given moisture level, the practice of rolling the fuel onto an existing fire does increase all pollutants significantly with the exception of particulate at the high moisture level. But even though the increase in emissions is significant, the absolute value changes are relatively small so that the higher emission from roll-on of orchard fuels is still less than emissions for most other crops being burned.

The emissions from the two evergreen species, avocado and olive, are generally higher than from deciduous species. Some of this difference is probably due to the higher moisture content but may be associated with the presence of the leaves. Removal of leaves from olive twigs and branches tended to reduce particulate and hydrocarbon but not carbon monoxide. From the limited data available it is not possible to draw conclusions on the contribution attached leaves might make to the total emissions from burning these crops.

The vast majority of particles from burning agricultural wastes are submicron in size. The mass median diameter of most particles is below .3 microns. The orchard fuels tend to yield smaller particles than do field crop fuels.

The use of back fires versus head fires significantly reduces particle size, the averages being .11 and .22 microns, respectively.

Drying the orchard fuels to a level below about 35 percent moisture does not alter particle size significantly. Within a given moisture level, however, the practice of rolling the fuel on an existing fire increases particle size significantly, the average size being a little more than doubled over particles from cold ignition fires. But even with the doubling, particles are still average less than .2 microns.

Finally, it seems appropriate to attempt to classify each crop within a reasonable emission factor range for each pollutant. Such a classification appears below with the stipulation that the factor range selected is based on the assumption that burning would be conducted under those conditions where lower emissions could be expected.

Within the herbaceous plant wastes there is considerable shifting in relative emission ranking from pollutant to pollutant with a few notable expections. Tule and mixed weeds are consistently at the low end of the scale for all pollutants and alfalfa asparagus, bean, oats, peas, and safflower are at the upper end of the scale for at least two of the three pollutants. All of the deciduous orchard crops are at the low end of the scale for all pollutants while avocado and olive are at the upper end, as noted above

Particulates, lbs/ton of fuel burned

<5	5-10	10-15	10-20	>20
Field and weeds				
tule	barley cotton rice mixed weeds	bean corn peas sorghum wheat ditch bank weeds	hay safflower	alfalfa asparagus oats
Orchard and vines				
apple apricot boysen-berry grape nectarine prune	almond cherry date fig peach pear walnut	olive	avocado	

Carbon monoxide, lbs/ton of fuel burned

	<40	40-80	80-100	100-120	120-140	>140
Field and weeds	tule	sorghum mixed weeds	rice ditch bank weeds	alfalfa asparagus barley corn wheat	oats	bean cotton hay peas safflower
Orchard and vines	almond apple apricot cherry nectarine peach prune	boysen- berry date fig grape pear walnut		avocado olive		

Hydrocarbon, lbs/ton of fuel burned

	<5	5-10	10-15	15-20	>20
Field and weeds	tule	sorghum mixed weeds cotton	rice ditch bank weeds	barley corn hay wheat	alfalfa asparagus bean oats peas safflower
Orchard and vines	apple boysen- berry nectarine prune	almond apricot date fig peach pear walnut	cherry	olive	avocado

RECOMMENDATIONS

From the results of this project it is again clear that the fine agricultural fuels, such as cereal grains and other herbaceous species, should be burned with back fires in order to minimize pollution levels. Although a high-to-low fuel moisture series of experiments were not conducted for these fuels, the factors obtained here for rice and barley at a low moisture level of about 12 percent agree with those obtained in an earlier project where moisture level was shown to be the most important factor affecting the yield of pollutants. Thus it should be restated that this class of fuels should be dried down to about 12 percent moisture before burning.

Prunings of deciduous orchard species should be dried down to about 35 percent moisture. Further drying reduces hydrocarbon levels but the absolute change is relatively small. It seems impractical to recommend additional drying for improvement in emissions of this pollutant alone.

If there is evidence that reasonably large quantities of the evergreen orchard species, avocado and olive, are being burned, then two courses of action may be in order: (1) categorically recommend, in an absence of data, that prunings be dried to at least 20 percent moisture; or (2) conduct additional experiments to determine the effect of drying on emissions and at the same time compare emissions with and without attached leaves.

Even though rolling orchard fuels onto an existing fire significantly increases emissions in most cases, it seems impractical to recommend that this practice be curtailed, at least with respect to particulate and hydrocarbon. The amounts of pollutant involved are relatively small and the high value is still lower than that of most other crops burned. Recommending against the roll-on technique might possibly be considered for carbon monoxide if large amounts of burning occur in an urban area where emissions of the gas from other sources are already at a critical level.

It is perhaps outside the scope of this project to make recommendations in regard to particle size distribution. Those recommended burning practices that reduce the amount of particulate matter also reduce the average size of the particles. But with the very small sizes involved, it is difficult to indicate whether the size reduction is a benefit.

BODY OF REPORT

INTRODUCTION

In order to determine the emissions from the burning of various agricultural wastes in California, arrangements were made between the State of California Air Resources Board (ARB) and the University of California, Riverside, (UCR) to burn a variety of such wastes at facilities of UCR's Statewide Air Pollution Research Center. The study was conducted in a burning tower that had been developed over the years for determining the nature and amounts of emissions from open burning of plant wastes generated in agricultural and forest operations.

In the present study, 312 fires were completed using 31 different field, vine, and orchard crops, and weeds. All of the wastes had been collected in the field by ARB staff and delivered to UCR.

METHODS AND MATERIALS

Facilities

Procedures for burning the wastes and sampling emissions were carried out in an out-of-doors burning tower and adjacent instrument building which has been described earlier by Darley et al (1). Some important modifications have since been made and are given in some detail in a recent publication of the National Academy of Sciences (3). A brief description of the tower is presented here.

The facility simulates open burning but channels the combustion products so that representative samples of gas and particles can be taken. The tower is in the form of an inverted funnel, 16 feet in diameter at the base, decreasing to 28 inches in a length of 20 feet, and topped with a stack 8 feet in length. The tower is erected above a table 8 feet in diameter, which is positioned on a scale with a maximum capacity of 125 pounds.

The sample site for gases, particulate, and for recording temperatures and airflow is in the stack about two feet below the top. Stack gases for analysis of total hydrocarbon, CO, and CO_2, were drawn through sample lines into the appropriate analyzers in the instrument building to give a continuous millivolt equivalent recording of concentrations. Part way through the study we had the opportunity of borrowing a newer model hydrocarbon analyser (Beckman 400) from the U. S. Environmental Protection Agency (EPA). When the new instrument was compared with our analyser (Beckman 109) it was obvious that the response of the 400 was more sensitive so that at given peaks in a fire, it registered a higher value. In computing emmision factors, the greater sensitivity had the net result of increasing the hydrocarbon yield by about 25 percent. After consulting with staff of both the ARB and EPA it was decided to complete this study and to conduct any future studies using only the new 400. Data from 19 fires were available wherein both hydrocarbon analysers were recording concentrations simultaneously. The relationship between the emissions calculated from these data using the method of least squares fit is shown in Figure 1. Hydrocarbon analyser number 1 is the model 109 and number 2 is the new model 400; the latter instrument was used for the major portion of the study. The relationship of emission values was quite linear throughout the range encountered in these fires, the correlation coefficient (r value) being .992.

Airflow was monitored with a 4-cup anemometer mounted in the stack. A shaft encoder is positioned on the end of the anemometer shaft, just outside of the stack. The encoder generates a millivolt signal by making and breaking a light beam through an 800-slot disc. One revolution of the

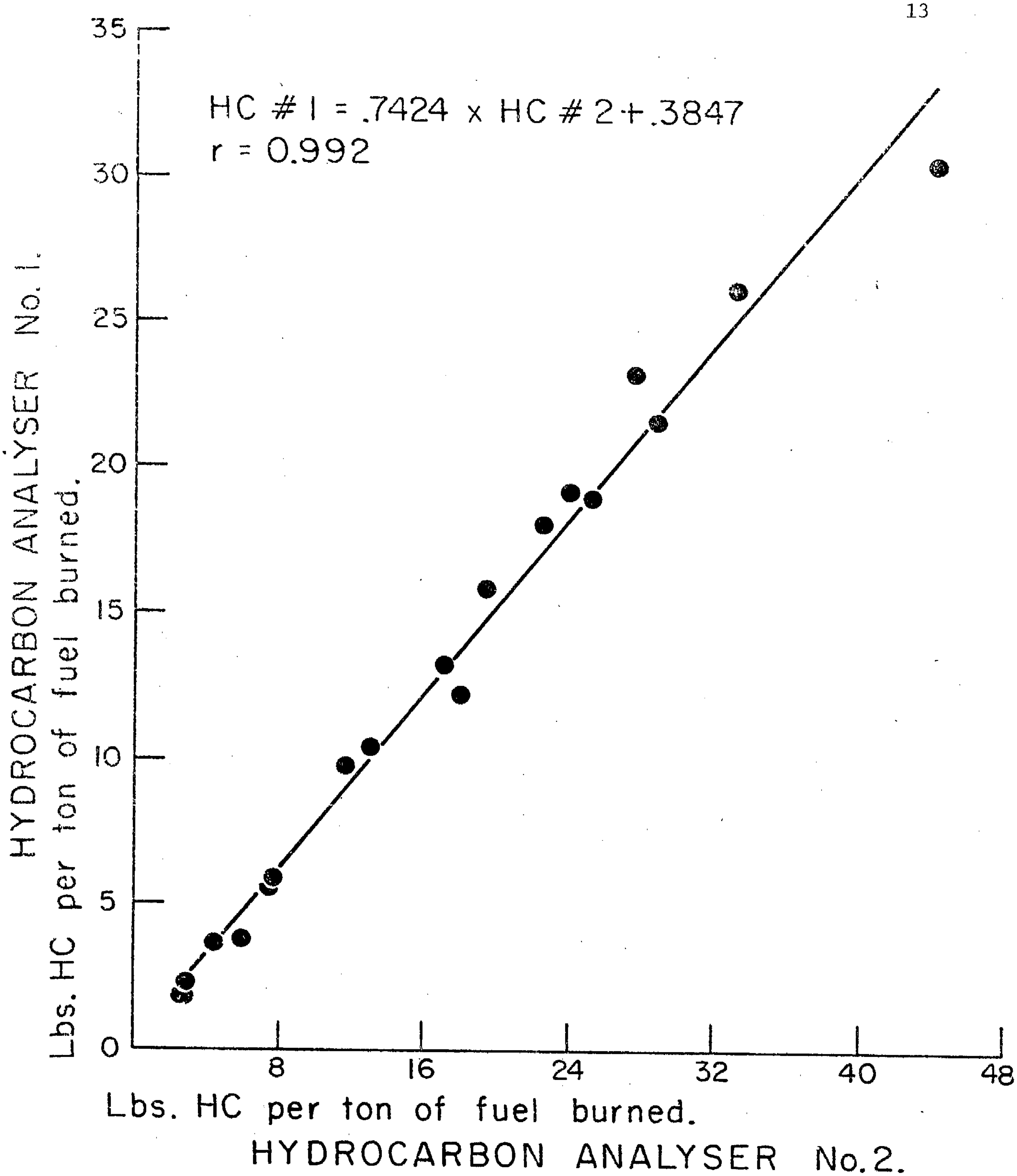


FIGURE 1. Comparison of hydrocarbon emissions in pounds per ton of fuel burned when measured simultaneously with hydrocarbon analyser #1 (Beckman 109) and hydrocarbon analyser #2 (Beckman 400).

shaft creates 800 pulses, and 3000 pulses per second generates the full-scale 50 mv signal. The maximum airflow encountered during the peak of the hottest agricultural fires is between 40-45 mv, or approximately 10,000 cubic feet per minute.

Recording of rate of weight lost during fires was accomplished by adapting a transducer to the actuating mechanism of the scale so that a change in weight generated a millivolt signal; 1 mv is equivalent to 1 pound and full range is 50 mv.

All recording instruments are connected to a data acquisition system which in turn is connected to the campus computer. The computer polls each recorder every 2.6 seconds and stores the millivolt response of each instrument on tape or discs. A computer program has been written from which the yield of pollutants in pounds per ton of fuel burned can be calculated using the data collected on temperature, gas concentration, and airflow.

Particulates are collected isokinetically on standard Type A-E glass fiber filters held in two modified HIVOL samplers positioned in series in the sample line and outside of the tower. A pneumatic controller senses differences in airflow in the stack and continuously adjusts a globe valve in the sample line so that isokinetic sampling is achieved. The sample volume is approximately 1/776th of the total flow through the stack. The principal use made of the isokinetic collection system has been to determine the total weight of particulate from given fuels to establish emission factors. In addition, for the present project a Sierra Instrument Company HIVOL 5-stage cascade impactor was used to determine particle size distribution from about half of the fires, representing all but one of the 31 fuels. The impactor was set up near the top of the tower so that samples were taken just above the opening of the stack. Particle cut-off sizes were determined for each stage by calculations based on the theory developed by Marple (4). A correction was made for a 50 cfm flow and a mass density of 0.9 g/cc was selected as a reasonable approximation.

Plant Residue Samples

Samples of plant residues to be burned were collected in the field at various intervals during 1974 and 1975 by ARB staff and delivered to the burning tower. Plant materials consisted of straws and stems of field crops, the pruned canes of vine crops, pruned branches of orchard crops, except date palms wherein the plant waste is the frond or leaf, and the whole plant of various weeds. In all, 31 crops and weeds were collected and are listed below in the appropriate category.

Field Crops (13)

Alfalfa
Asparagus
Barley
Bean
Corn
Cotton (field trash)
Hay (wild)
Oats
Pea
Rice
Safflower
Sorphum
Wheat

Vine crops (2)

Boysenberry
Grape

Orchard crops (13)

Almond
Apricot
Apple
Avocado
Cherry
Date Palm
Fig
Nectarine
Olive
Peach
Pear
Prune
Valnut

Weeds (3)

Ditch Bank
Mixed
Tules

Burning Procedures

Field crops:-- Most of the field crops were burned with both head and back fires. Head fires are defined as burning with the wind or up-slope. Backfires are defined as burning against the wind or down-slope.

The two fire types were simulated in the tower by placing the fuel on a rack set at a given slope. It was intended that the slope of all fires be 25 percent but early in the project many fires were inadvertently conducted at a 15 percent slope. Where there was sufficient fuel, fires were repeated at a 25 percent slope. Some field crop fires were conducted with the fuel laid flat on the burning table; windrows were used for cotton field wastes.

Since most of the field crop material was collected after harvest it was relatively dry and was burned as received. Thus, most fuels were burned at less than 12 percent moisture on a dry weight basis (dwb). A few fuels had a slightly higher moisture content and one, sorghum, ranged from 29 to 66 percent moisture (dwb). No attempt was made to compare emissions at different moisture levels because the principles derived from such a procedure were well established in an earlier ARB project (2).

In general, two head fires and two back fires were conducted for each crop using about 6-8 pounds of fuel for each fire.

Orchard crops: -- Orchard wastes were burned in piles, the fires being conducted in pairs. The first fire of a pair was started "cold," by which we mean that there were no hot coals or preexisting fire on the table and the fuel was ignited at the bottom of the pile with a large propane torch. The second fire of a pair was ignited by rolling the pile of fuel onto the glowing embers of the first fire. Thus, the two fires of a pair are labeled "cold" and "roll-on", respectively. After roll-on, two or three minutes lapsed before the pile started to flame. The reason for using the roll-on method was to simulate in some way the field practice of placing residues on the hot coals of a previous fire. In most cases, 16 fires were conducted for each orchard species; four pairs of fires at a high moisture level and four pairs at a lower moisture level. With date palm only four single fires were conducted at a low moisture.

When the prunings of orchard crops were received, they had been freshly cut and moisture was quite high, varying from 47 percent (dwb) in necatrine to 108 percent in fig. Sixty to 80 percent moisture was usual for most species. The plan was to burn four pairs of fires at about 35 percent moisture (dwb) and four pairs at about 20 percent or lower. Thus it was necessary to allow the fuels to dry down for a period of time and to monitor the rate of drying.

For the 10 deciduous species, that is those that lose their leaves in the fall, the following methods were used. Shortly after the prunings were received, each species was separated into 16 piles of 45 pounds each. Care was taken to assure that the size distribution of branches was uniformly represented in each pile. A few complete branches were cut into small pieces, placed in a drying oven at 104 C, and percentage moisture determined on a dry weight basis. Two five-pound samples from each species were similarly selected and designated as master moisture samples. The two master samples were set among the 16 45-pound piles and weighed regularly to monitor the rate of moisture loss. The weights that the master sample should reach when they were first at about 35 percent moisture (dwb) and then later at about 20 percent were calculated. The piles were allowed to dry down until the predicted weights of the master samples were attained. On the day of the burn the moisture of representative branches of each pile was determined and this is the value that was recorded. Whereas we had hoped that the master moisture sample technique would be a good indication of the moisture in the piles, in actual practice this proved not to be the case. The moisture content of the piles was generally higher than the master samples and we did not acheive as great a difference in the two series of moisture levels as we had planned for. In retrospect, it would have been better to organize the piles so that they could have been weighed at regular intervals and burned when the desired water loss from each pile had been reached. Our concern was to minimize handling of the piles so as not to break branches and twigs which would alter composition and drying rate from that obtaining had the prunings been left in the field.

In general about 2 months lapsed from time of delivery of the prunings until they were dry enough to burn at the higher moisture level and another 1-1/2 to 3 months lapsed before the second set of fires was conducted at the lower moisture level.

The two evergreen species, avocado and olive, were handled somewhat differently than the deciduous group described above because of the presence of leaves. For the first burn at the higher moisture level, the complete lot of prunings as delivered to us was allowed to dry until the leaves and small twigs appeared to be dry enough to burn. Eight piles of 45 pounds each were then constructed and burned. Two months later the second group of eight piles were constructed and burned. Samples were taken for moisture determination just before each burn. For avocados the sample was divided into leaves and twigs, branches from 1/2-1 inch in diameter, and branches from 1-3 inches in diameter. The olive branches were somewhat smaller and samples for moisture determination were divided into the two categories of leaves and twigs, and branches.

Vine crops: --The boysenberry canes were quite dry when received, and only four single piles were burned. The grapes were sufficiently moist (82 percent moisture - dwb) to follow the system of cold and roll-on fires described for orchard fuels.

Weeds: -- The weeds were dry when received and no attempt was made to determine the effect of moisture levels on emissions. Weeds were burned by methods similar to those used for field crops except for the tules. In one set of fires the tule plants were piled. In a second set the plants were held vertically in a special rack so that they were standing much as they might in their natural position in the field. The rack had been designed for the purpose of holding sugar cane stems and leaves erect to simulate the position of the plants in field burning.

RESULTS AND DISCUSSION

Emissions of Particulates, Carbon Monoxide, and Hydrocarbons.

Emissions of particulates, CO, and hydrocarbons in terms of pounds per ton of fuel burned for all 312 fires are given in Table 1. Crops burned are arranged alphabetically within the broad categories of field, vine, and orchard crops and weeds; type of fire and moisture level are also shown.

Before discussing the data in Table 1, it might be appropriate to point out in summary that there was a considerable difference in emissions from burning the two classes of agricultural wastes, i.e., field crops, including weeds, versus orchard crops, including boysenberries and grapes. The average emissions of all plant material within these classes at the indicated average fuel moisture (dwb) is shown as follows:

	Average fuel moisture	Average emissions, pounds per ton of fuel burned		
		Part.	CO	HC #2
Field crops (including weeds)	12.3	18.3	113.6	17.3
Orchard crops (including vines)	40.3	8.7	58.6	11.1
	23.7	5.4	54.3	7.5

Table 1. Emissions of Particulate Carbon Monoxide and Hydrocarbons from Burning Residues from Various Field, Vine and Orchard Crops, and Weeds

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Field Crops							
Alfalfa	Head-25[a]		10.4	41.5[b]	103.7	...	33.9
			10.4	48.0	107.8	...	38.2
		av.	10.4	44.8	105.8		36.1
	Back-25		10.4	26.1[b]	125.3	...	38.0
			10.4	31.4	112.4	...	35.1
		av.	10.4	28.8	118.9	...	36.6
Asparagus fern (baled)	Head-15		10.9	24.5	98.6	13.1	
			11.6	27.9	108.9	14.9	
		av.	11.3	26.2	103.8	14.0	(18.3)[c]
	Back-15		11.7	26.1	95.9	12.9	
			10.9	29.7	107.3	15.0	
		av.	11.3	27.9	101.6	14.0	(18.3)
	Head-25		10.5	34.4[b]	90.4	15.8	19.4
			10.5	34.7	121.3	18.9	25.2
		av.	10.5	34.6	105.9	17.4	22.3
	Back-25		10.5	29.5	145.4	18.0	22.5
			10.5	25.4[b]	118.1	13.2	17.1
		av.	10.5	27.5	131.8	15.6	19.8
(whole plants)	Flat		12.0	22.3	79.6	9.2	(11.9)

[a]15 or 25 refers to percent slope used.

[b]Smoke was sampled for particle size distribution.

[c]HC yields in parentheses were calculated from data given in Figure 1.

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned Part.	CO	HC#1	HC#2
Barley	Head-15		8.6	6.6[b]	85.1	5.5	
			9.1	9.4[b]	102.5	6.1	
			11.8	11.4	91.6	4.1	
		av.	9.8	9.1	93.1	5.2	(6.5)
	Back-15		10.5	7.1[b]	80.4	5.6	
			8.7	7.8[b]	102.5	5.5	
			10.1	9.6	110.7	6.6	
		av.	9.8	8.2	97.9	5.9	(7.4)
	Head-25		10.0 est.	14.6	148.2	17.1	
			10.0 est.	28.5	152.3	22.2	
			8.1	21.3[b]	156.5	23.2	27.6
		av.	9.4	21.5	152.3	20.8	(27.5)
	Back-25		10.0 est.	7.8	113.3	10.1	
			10.0 est.	8.6	112.7	11.9	
		av.	10.0	8.2	113.0	11.0	(14.3)
	Flat		9.1	7.7[b]	91.7	5.6	
			10.0	6.8[b]	92.7	4.0	
			10.0	9.4	96.9	4.4	
		av.	9.7	8.0	93.7	4.7	(5.8)
Bean (red)	Head-15		12.5	20.2[b]	174.4	20.9	
			11.6	19.5[b]	70.0	7.9	
			11.0	13.0	142.7	13.8	
		av.	11.7	17.7	129.0	14.2	(18.6)
	Back-15		12.3	15.6[b]	155.5	16.8	
			11.2	16.4[b]	156.5	14.6	
			9.8	11.6	139.1	11.9	
		av.	11.1	14.5	150.4	14.4	(18.9)
	Head-25		12.4	45.7[b]	193.1	37.5	
			9.7	40.4[b]	179.1	30.4	44.2
		av.	11.0	43.0	186.1	34.0	(45.3)
	Back-25		13.7	11.3[b]	183.9	19.5	
			9.7	12.4[b]	149.9	19.1	24.0
		av.	11.7	11.9	166.9	19.3	(25.5)

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned: Part.	CO	HC#1	HC#2
Corn	Head-15		16.8	17.4[b]	115.5	13.6	
			14.5	16.1[b]	107.9	13.6	
			12.7	15.2	142.7	13.8	
			13.4	12.7	99.9	10.6	
		av.	14.4	15.4	116.5	12.9	(16.9)
	Back-15		16.9	15.2[b]	108.6	12.7	
			10.8	13.2[b]	95.6	10.7	
			14.1	11.5	97.8	10.3	
		av.	13.9	13.3	100.7	11.2	(14.6)
	Head-25		9.0	15.0	120.5	15.7	
			9.5	12.4[b]	89.6	9.6	
		av.	9.3	13.7	105.1	12.7	(16.6)
	Back-25		7.6	15.1	110.3	14.2	
			11.7	13.2[b]	102.4	11.0	
		av.	9.7	14.2	106.4	12.6	(16.5)
Cotton	Windrow		14.4	10.7	182.8	4.3	
			14.7	6.2[b]	169.0	4.3	
		av.	14.6	8.5	175.9	4.3	(5.3)
Hay (Wild)	Head-25		10.4	27.4[b]	137.4	...	21.8
			10.9	36.7	139.7	...	22.5
		av.	10.7	32.1	138.6	...	22.2
	Back-25		10.1	16.5[b]	155.3	...	18.4
			11.1	17.4	144.4	...	14.7
		av.	10.6	17.0	149.9	...	16.6

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
			Part.	CO	HC#1	HC#2
Oats	Head-15	11.3	18.4[b]	121.4	9.0	
		9.1	23.5[b]	154.0	17.8	
		10.8	19.7	149.2	15.5	
		av. 10.4	20.5	141.5	14.1	(18.5)
	Back-15	11.8	19.3	124.8	10.5	
		9.2	22.2[b]	135.8	12.4	
		11.2	20.3[b]	130.0	13.1	
		10.2	22.0[b]	156.4	14.4	
		av. 10.6	21.0	136.8	12.6	(16.5)
	Head-25	7.1	44.8[b]	141.6	25.2	
		9.6	43.8	132.5	26.1	33.3
		av. 8.4	44.3	137.1	25.7	(34.1)
	Back-25	8.1	17.9	134.0	18.3	
		7.6	21.5[b]	124.0	18.1	
		av. 7.9	19.7	129.0	18.2	(24.0)
	Flat	9.5	19.6[b]	131.9	11.6	
		10.5	21.9	138.1	16.5	
		12.7	21.5[b]	135.4	10.4	
		av. 10.9	21.0	135.1	12.8	(16.7)
Pea Vines	Head-25	9.8	32.5	147.3	...	39.1
		9.8	29.6[b]	147.4	...	37.4
		av. 9.8	31.1	147.4		38.3
	Back-25	9.8	14.3	157.4	...	31.8
		9.8	14.3[b]	143.2	...	29.0
		9.8	14.3	150.3		30.4
Rice	Head-15	10.1	14.7[b]	95.7	8.4	(10.8)
	Back-15	11.7	8.3[b]	74.1	5.5	(6.9)
	Head-25	9.4	9.9	122.6	9.1	(11.7)
	Back-25	10.2	6.3[b]	87.4	8.0	(10.3)

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Safflower	Head-15		16.9	14.7[b]	125.9	16.6	
			10.9	12.4[b]	130.1	9.3	
			14.4	23.8	177.9	26.0	
		av.	14.1	17.0	144.6	17.3	(22.8)
	Back-15		18.3	14.6[b]	122.6	13.7	
			12.2	24.9[b]	139.2	28.3	
			12.2	20.8	165.2	24.4	
		av.	14.2	20.1	142.3	22.1	(29.3)
Sorghum	Head-25		66.0	11.8[b]	68.3	5.1	
			43.9	31.7[b]	79.2	6.8	
		av.	55.0	21.8	73.8	6.0	(7.6)
	Back-25		46.6	13.4[b]	80.9	7.0	
			29.3	13.4	79.2	7.9	
		av.	38.0	13.4	80.1	7.5	(9.6)
Wheat	Head-15		7.6	9.6[b]	91.3	5.5	
			8.4	12.6	105.0	6.4	
			9.7	12.2	110.2	6.8	
		av.	8.6	11.3	102.2	6.2	(7.8)
	Back-15		7.8	7.9[b]	82.1	3.2	
			8.6	9.7[b]	95.9	5.3	
			8.5	12.5[b]	89.0	6.6	
			9.7	10.6[b]	100.7	5.7	
		av.	8.7	10.2	91.9	5.2	(6.5)
	Head-25		7.2	20.5[b]	143.1	24.8	
			10.7	35.5	167.1	21.6	28.8
		av.	9.1	28.0	155.1	23.2	(30.7)
	Back-25		7.5	11.8[b]	110.8	15.2	
			6.6	10.6	110.7	10.4	13.0
		av.	7.1	11.2	110.8	12.8	(16.7)
	Flat		7.4	7.4[b]	84.1	3.6	
			8.9	10.7	95.0	5.6	
			11.6	11.4[b]	105.8	6.2	
		av.	9.3	9.8	94.7	5.1	(6.4)

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
			Part.	CO	HC#1	HC#2
Vine Crops						
Boysenberry	Pile	11.0	3.8[b]	64.3	1.8	
		11.0	3.9[b]	62.9	1.0	
		12.0	3.6	43.7	0.8	
		12.0	3.7	51.7	0.6	
	av.	11.5	3.8	55.7	1.1	(1.0)
Grape	Cold	40.7	6.6[b]	36.9	...	6.6
	Roll-on	40.0	8.2	49.9	...	10.4
	Cold	39.6	7.4[b]	46.1	...	7.6
	Roll-on	37.5	8.2[b]	50.2	...	9.2
	Cold av.	[39.5]	7.0	41.5	...	7.2
	Roll-on av.		8.2	50.1	...	9.8
	Cold	24.0	3.4[b]	46.2	...	2.7
	Roll-on	26.1	5.2	58.3	...	5.4
	Cold	22.8	3.8[b]	44.4	...	3.3
	Roll-on	22.3	5.1[b]	59.3	...	3.7
	Cold av.	[23.8]	3.6	45.3	...	3.0
	Roll-on av.		5.2	58.8	...	4.6

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Orchard Crops							
Almonds	Cold		39.7	4.4	35.1	...	7.4
	Roll-on		...	6.8	47.0	...	10.6
	Cold		38.7	4.1[b]	35.3	...	6.6
	Roll-on		38.4	5.5[b]	47.0	...	9.0
	Cold		39.3	3.8[b]	44.4	...	7.4
	Roll-on		38.2	6.2	61.7	...	10.4
	Cold		39.5	3.4	34.8	...	6.1
	Roll-on		38.6	6.6[b]	45.4	...	11.9
	Cold	av.	[38.9][c]	3.9	37.4	...	6.9
	Roll-on	av.		6.3	50.3	...	10.5
	Cold		28.1	3.4[b]	21.1	...	4.3
	Roll-on		24.8	4.5	30.2	...	6.6
	Cold		25.4	3.6[b]	23.4	...	3.2
	Roll-on		25.4	5.3	40.5	...	6.7
	Cold		27.2	3.7	10.3	...	1.3
	Roll-on		26.6	5.2[b]	35.1	...	8.0
	Cold		26.0	3.7	25.5	...	3.3
	Roll-on		27.2	7.0[b]	40.1	...	7.8
	Cold	av.	[26.3]	3.6	20.1	...	3.0
	Roll-on	av.		5.5	36.5	...	7.3

[c] Since fires were conducted on consecutive days, the average of all eight moisture samples is given.

Table 1. (Continued)

Crop	Type of Fire		% Moisture dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Apple	Cold		27.9	3.8[b]	32.3	...	3.5
	Roll-on		34.4	4.8	37.7	...	6.2
	Cold		28.2	4.4	31.4	...	3.6
	Roll-on		38.6	5.1[b]	44.6	...	6.7
	Cold		34.7	4.3	36.6	...	3.0
	Roll-on		30.4	5.5[b]	48.1	...	5.1
	Cold		33.9	4.5[b]	31.9	...	3.5
	Roll-on		33.7	4.5	36.1	...	4.5
	Cold	av.	[32.7]	4.3	33.1	...	3.4
	Roll-on	av.		5.0	41.6	...	5.6
	Cold		20.7	3.3[b]	28.0	...	2.5
	Roll-on		21.6	4.1	62.7	...	5.8
	Cold		23.7	4.1	27.2	...	2.4
	Roll-on		17.9	3.6[b]	62.8	...	4.7
	Cold		16.6	3.5	26.3	...	2.3
	Roll-on		23.5	4.2[b]	72.6	...	6.8
	Cold		20.7	4.2	26.5	...	2.2
	Roll-on		20.4	3.9	60.4	...	5.9
	Cold	av.	[20.6]	3.8	27.0	...	2.4
	Roll-on	av.		4.0	64.6	...	5.8

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Apricot	Cold		42.0	5.7[b]	38.4	4.9	
	Roll-on		42.8	7.8	65.9	8.3	
	Cold		37.9	4.6	43.6	4.1	
	Roll-on		42.5	6.7[b]	57.6	5.9	
	Cold		40.6	6.5	51.7	5.5	
	Roll-on		39.7	11.7[b]	70.6	11.2	
	Cold		36.3	8.1[b]	60.6	6.4	
	Roll-on		39.4	9.6	68.9	11.6	
	Cold	av.	[40.2]	6.2	48.6	5.2	(6.5)
	Roll-on	av.		9.0	66.8	9.3	(12.0)
	Cold		29.9	4.2	23.8	...	2.4
	Roll-on		28.6	7.4[b]	52.0	...	7.7
	Cold		26.2	4.2[b]	35.8	...	3.3
	Roll-on		...	6.2	46.4	...	5.7
	Cold		24.6	4.1[b]	33.5	...	3.4
	Roll-on		25.8	4.9	44.3	...	5.5
	Cold		26.6	4.1	30.3	...	3.6
	Roll-on		29.0	5.1[b]	55.4	...	5.3
	Cold	av.	[27.2]	4.2	30.9	...	3.2
	Roll-on	av.		5.9	49.5	...	6.1

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis: lvs., twigs	branches ½-1"	branches 1-3"	Emissions, lbs. per ton fuel burned: Part.	CO	HC#1	HC#2
Avocado	Cold	33.1	84.7	86.8	22.2	126.9	...	34.8
	Roll-on	...	89.3	77.7	24.6[b]	134.3	...	38.2
	Cold	31.5	102.7	81.0	21.9[b]	126.8	...	36.3
	Roll-on	...	81.4	73.7	24.2	116.8	...	36.8
	Cold av.	[32.3]	[89.5]	[79.8]	22.1	126.9	...	35.6
	Roll-on av.				24.4	125.6	...	37.5
	Cold	17.4	26.1	45.2	18.1[b]	112.0	...	26.5
	Roll-on	15.7	26.5	45.1	17.8[b]	101.7	...	28.2

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Cherry	Cold		42.3	10.7[b]	41.9	...	12.2
	Roll-on		37.7	13.8	49.3	...	14.7
	Cold		37.3	7.3[b]	36.6	...	7.2
	Roll-on		40.3	10.9	49.2	...	12.9
	Cold		38.9	6.6	43.6	...	8.8
	Roll-on		47.2	8.5[b]	57.9	...	11.2
	Cold		42.8	6.4	40.1	...	7.8
	Roll-on		42.4	10.8[b]	62.4	...	15.4
	Cold	av.	[41.1]	7.8	40.6	...	9.0
	Roll-on	av.		11.0	54.7	...	13.6
	Cold		30.3	4.9[b]	31.0	...	6.9
	Roll-on		33.0	7.0	46.0	...	10.0
	Cold		27.4	5.4	32.1	...	7.2
	Roll-on		30.5	8.3	45.8	...	11.3
	Cold		29.6	5.1	35.4	...	8.2
	Roll-on		31.6	8.2	52.6	...	13.0
	Cold		31.5	4.8	28.0	...	5.5
	Roll-on		37.5	8.2[b]	48.0	...	12.8
	Cold	av.	[31.4]	5.1	31.6	...	7.0
	Roll-on	av.		7.9	48.1	...	11.8

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis		Emissions, lbs. per ton fuel burned			
		pinnae	petiole	Part.	CO	HC#1	HC#2
Date Palm	Pile	11.2	15.2	7.1[b]	48.3	...	5.4
		11.3	15.3	6.4	48.0	...	5.7
		11.6	16.7	13.6[b]	61.1	...	9.7
		10.8	14.3	10.8	66.6	...	6.8
	av.	11.2	15.4	9.5	56.0		6.9

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned: Part.	CO	HC#1	HC#2
Fig	Cold	40.8	5.3[b]	48.6	...	7.4
	Roll-on	46.8	14.6	89.9	...	22.1
	Cold	36.5	4.9	41.0	...	5.0
	Roll-on	41.5	10.0[b]	83.5	...	16.1
	Cold	38.6	4.8[b]	44.2	...	7.5
	Roll-on	36.0	8.1	66.5	...	14.7
	Cold	39.4	6.0	44.5	...	9.4
	Roll-on	40.2	10.0[b]	75.4	...	18.9
	Cold	av. [40.0]	5.3	44.6		7.3
	Roll-on	av.	10.6	78.8		18.0
	Cold	19.5	4.9[b]	40.2	...	4.5
	Roll-on	19.8	7.8	63.1	...	10.4
	Cold	21.2	5.0	36.6	...	4.7
	Roll-on	21.1	11.9[b]	71.8	...	9.8
	Cold	19.0	5.4	43.6	...	6.2
	Roll-on	20.5	6.4[b]	49.1	...	7.8
	Cold	21.9	5.8[b]	38.3	...	5.5
	Roll-on	18.6	8.0	71.6	...	10.1
	Cold	av. [20.2]	5.3	39.7	...	5.2
	Roll-on	av.	8.5	63.9	...	9.5

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
			Part.	CO	HC#1	HC#2
Nectarine	Cold	35.3	4.9	37.3	...	4.0
	Roll-on	37.2	4.5[b]	40.3	...	5.0
	Cold	34.5	4.1[b]	37.8	...	5.1
	Roll-on	37.6	5.2	39.7	...	5.8
	Cold	34.2	3.2[b]	26.0	...	2.8
	Roll-on	28.4	3.8	30.3	...	4.6
	Cold	30.8	3.2	24.4	...	3.1
	Roll-on	35.8	4.7	33.2	...	5.6
	Cold av.	[34.2]	3.9	31.4	...	3.8
	Roll-on av.		4.6	38.9	...	5.3
	Cold	31.3	3.9[b]	29.1	...	3.0
	Roll-on	29.7	4.9	33.5	...	4.2
	Cold	28.6	4.5	30.2	...	3.4
	Roll-on	32.0	5.1[b]	36.4	...	4.8
	Cold	29.7	3.8	30.0	...	3.0
	Roll-on	27.8	4.8[b]	32.0	...	3.6
	Cold av.	[29.9]	4.1	29.8	...	3.1
	Roll-on av.		4.9	33.7	...	4.2

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis: lvs., twigs	% Moisture, dry wt. basis: branches	Emissions, lbs. per ton fuel burned: Part.	CO	HC#1	HC#2
Olive	Cold	22.1	42.5	12.3	111.1	...	15.0
	Roll-on	19.2	45.5	15.3[b]	108.0	...	18.8
	Cold	25.8	45.8	12.7[b]	105.4	...	16.9
	Roll-on	21.6	45.9	12.7	96.3	...	16.6
	Cold	25.7	42.6	9.9[b]	100.8	...	15.0
	Roll-on	...	48.6	19.3	118.4	...	22.6
	Cold	22.2	45.7	12.6	98.9	...	14.4
	Roll-on	28.4	46.5	16.4[b]	111.8	...	19.6
	Cold av	[23.6]	[45.4]	11.9	104.1	...	15.4
	Roll-on av			15.9	108.6	...	19.4
	Cold	11.1	34.9	13.6[b]	91.6	...	14.0
	Roll-on	12.2	31.1	12.9	171.9	...	25.3
	Cold	11.1	30.6	12.0	84.3	...	14.6
	Roll-on	11.8	28.3	11.0[b]	136.0	...	23.3
	Cold	9.6	33.1	8.9	88.3	...	10.0
	Roll-on	11.1	33.2	11.2[b]	127.0	...	19.0
	Cold av	[11.2]	[31.9]	11.5	88.1		12.9
	Roll-on av			11.7	145.0		22.5
	Cold	14.9[c]	30.8	8.2	134.2	...	17.1
	Roll-on	12.6	30.5	7.4	146.1	...	17.8

[c]For this pair of fires, all leaves were removed and only twigs and branches were burned.

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Peach	Cold		35.5	4.8[b]	43.2	4.5	
	Roll-on		38.0	4.2	49.3	4.9	
	Cold		44.3	5.6	43.6	4.3	
	Roll-on		48.6	7.5[b]	45.8	8.6	
	Cold		50.7	4.6[b]	46.3	5.4	
	Roll-on		42.5	4.8	48.7	6.2	
	Cold		42.1	6.2	52.6	5.7	
	Roll-on		40.6	6.1[b]	50.2	5.9	7.7
	Cold	av.	[42.8]	5.3	46.4	5.0	(6.2)
	Roll-on	av.		5.7	48.5	6.4	(8.1)
	Cold		25.5	5.2	36.2	...	2.9
	Roll-on		26.6	5.9[b]	44.1	...	5.8
	Cold		24.4	5.5[b]	34.9	...	3.0
	Roll-on		24.0	5.2	41.8	...	3.4
	Cold		24.2	9.6[b]	37.9	...	2.7
	Roll-on		24.1	8.2	61.3	...	6.3
	Cold		24.6	5.7	35.0	...	3.2
	Roll-on		25.0	7.6[b]	56.0	...	6.5
	Cold	av.	[24.8]	6.5	36.0		3.0
	Roll-on	av.		6.7	50.6		5.5

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Prune	Cold		29.6	2.8[b]	35.3	1.4	(1.4)
	Roll-on		27.6	3.3	53.1	3.0	(3.5)
	Cold		35.4	4.3	39.0	1.9	(2.0)
	Roll-on		33.9	3.6[b]	45.8	2.8	(3.3)
	Cold		26.3	3.9	31.7	2.3	2.9
	Roll-on		28.2	2.9[b]	39.0	3.7	4.4
	Cold		26.4	3.3[b]	28.6	1.9	2.6
	Roll-on		36.4	4.8	47.9	5.6	7.4
	Cold	av.	[30.5]	3.6	33.7	1.9	2.2
	Roll-on	av.		3.7	46.5	3.8	4.7
	Cold		20.9	2.8	37.5	...	2.0
	Roll-on		21.4	3.2[b]	45.8	...	3.6
	Cold		21.1	2.4[b]	31.8	...	1.3
	Roll-on		21.6	3.5	40.7	...	3.5
	Cold		18.9	...	33.3	...	1.7
	Roll-on		20.1	4.0[b]	31.6	...	3.9
	Cold		18.4	3.5[b]	26.3	...	2.1
	Roll-on		19.1	3.5	39.1	...	3.7
	Cold	av.	[20.2]	2.9	32.2	...	1.8
	Roll-on	av.		3.6	39.3	...	3.7

Table 1. (Continued)

Crop	Type of Fire	% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
			Part.	CO	HC#1	HC#2
Walnut	Cold	43.4	4.9	42.9	...	5.8
	Roll-on	45.5	6.6[b]	57.3	...	8.1
	Cold	40.6	6.7[b]	44.0	...	7.1
	Roll-on	49.4	7.3	54.6	...	8.5
	Cold	44.7	6.1[b]	42.9	...	7.1
	Roll-on	46.1	8.8	63.6	...	13.6
	Cold	45.4	7.5	47.7	...	9.7
	Roll-on	46.6	10.3[b]	66.6	...	17.3
	Cold av.	[45.2]	6.3	44.4	...	7.4
	Roll-on av.		8.3	60.5	...	11.9
	Cold	31.5	5.5[b]	40.7	...	5.2
	Roll-on	36.5	5.7	42.9	...	6.6
	Cold	31.6	4.8	40.2	...	5.2
	Roll-on	36.6	5.5[b]	44.1	...	6.6
	Cold	38.1	6.0	50.2	...	9.3
	Roll-on	32.5	4.3[b]	38.9	...	5.6
	Cold	...	5.6[b]	42.0	...	5.3
	Roll-on	30.0	6.1	45.7	...	6.7
	Cold av.	[33.8]	5.5	43.3	...	6.3
	Roll-on av.		5.4	42.9	...	6.4

Table 1. (Continued)

Crop	Type of Fire		% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
				Part.	CO	HC#1	HC#2
Weeds							
Ditch Bank	Head-25		11.1	17.9[b]	115.9	12.3	...
			11.1	17.4	110.6	12.2	18.0
		av.	11.1	17.7	113.3	12.3	(16.1)
	Back-25		11.1	14.0	98.9	11.7	
			11.1	11.7[b]	89.0	9.7	11.6
		av.	11.1	12.9	94.0	10.7	(13.9)
	Flat		13.8	17.4	92.2	10.6	
			13.8	15.1	77.8	6.7	
		av.	13.8	16.3	85.0	8.7	(11.2)
	Piles		13.8	35.4[b]	70.8	15.7	
			13.8	20.8	69.1	11.2	
		av.	13.8	28.1	70.0	13.5	(17.7)
Mixed	Piles		11.2	9.0	63.8	4.1	
			11.2	11.2	88.4	5.5	
			11.2	6.7	72.2	3.2	
			11.2	6.5	66.1	3.8	
		av.	11.2	8.4	72.6	4.2	(5.1)
Tules	Piles		17.4	3.9[b]	29.8	...	1.8
			16.0	5.6	37.2	...	1.3
		av.	16.7	4.8	33.5		1.6
	Rack[d]		15.6	4.7[b]	33.6	...	2.0
			12.8	4.8	36.7	...	1.6
		av.	14.2	4.8	35.2		1.8

[d] Stems of the tules were held vertically in a special metal rack.

Even at higher moisture levels emissions of all pollutants were less from burning orchard crops than from burning field crops.

Particulates: -- Field crops and weeds will be discussed together because both are generally classed as fine herbaceous fuels (as contrasted to woody fuels), and weeds often grow along with field crops. Also weeds in non-cultivated areas adjacent to crops may be burned at the same time the crop residues are burned.

Crops with the highest yield of particulate matter were alfalfa, bean, and oats where over 40 pounds per ton of fuel burned were emitted when head firing was used at the 25 percent slope. Less than 10 pounds were emitted by barley, cotton, field trash, and rice when using back or flat firing; emissions from wheat were only slightly higher. Less than 5 pounds were emitted when burning tule stems, either in piles or standing erect. Ditch bank weeds produced considerably more particulate when burned in piles than when either head or back firing was employed.

Those crops contributing substantially more particulate than the average noted above included asparagus, wild hay and pea vines. In most cases, back fires produced less particulate than head fires, the difference being almost a factor of 3 with barley, bean, and wheat. Exceptions to this trend were asparagus, oats, and safflower at the 15 percent slope and corn at the 25 percent slope.

In those field crops where both the 15 and 25 percent slopes was used, head fires at 15 percent produced more particulate than head fires at 25 percent. There was little or no difference in emissions when comparing back fires at the two slopes. These results illustrate the inadvisability of using head fires because a small increase in slope (or wind speed) can cause marked increases in emissions, whereas small changes in back fire slope do not alter the yield of particulates very much. Just the fact that a back fire is being used appears to minimize emissions.

The consistently high particulate emissions from alfalfa and asparagus indicate that this may be an inherent characteristic of these two crops. Fuel manipulation, even when the fuel was relatively dry did not result in any great reduction as was the case with all other field crops.

Since particulate emissions from orchard crops, including boysenberry and grape vines, were so low, there was not a wide range in yield when moisture level and type of fire were manipulated. In many cases, emissions averaged less than 5 pounds of particulate per ton of fuel burned, and in only 5 crops (avocado, cherry, fig, olive, and pear) did fires emit more than 10 pounds of particulate. Avocado, one of the two evergreen species, yielded 22.1 and 24.4 pounds at the higher moisture level for cold and roll fires, respectively, and about 18 pounds in each cold and roll-on fire at the lower moisture level. Yields from the other four species, including olive, the other evergreen, were more nearly 10 pounds.

In general, drying orchard crops from a level of about 35 percent moisture (dwb) to something near 25 percent tended to reduce particulate emissions but the change was not significant in either the cold or roll-on fires when averages from the 11 deciduous orchard crops (deleting data from avocado and olive) were compared. Similarly, rolling the pile of fuel onto an existing fire tended to increase particulate emissions. At the high moisture level the increase was not significant, whereas at the lower moisture the increase from 4.6 pounds (cold) to 5.8 pounds (roll-on) was significant at the 95 percent confidence level. Even so, this relatively small increase would not seem to justify discouraging roll-on type fires where particulates are the pollutant of principal concern. With fig, at the higher moisture level, rolling on piles doubled the particulate emissions (5.3 to 10.6 pounds) but more fires would have to be run to determine if this difference is characteristic of the species. At first, one might guess that the moisture being somewhat greater than 35 percent was responsible for the increase, but with peach where the moisture was even higher, there was only a slight increase in emissions between cold and roll-on fires (5.3 and 5.7 pounds, respectively).

For all fuels except avocado, it appears that drying down to at least 35 percent moisture would minimize particulate emissions to acceptable levels. Whereas rolling piles onto existing fires tends to increase emissions, the change is generally small and the practice should not necessarily be discouraged. Although the experiments were not run, it appears that it would be necessary to dry down avocado so that the smaller branches were somewhat below 25 percent before a reduction in particulate emissions comparable to that found with other species could be achieved.

Carbon monoxide: -- Emissions of carbon monoxide from field crops, including weeds, ranged from a low of 33.5 pounds per ton of fuel burned with tules to a high of 186.1 pounds with 25 percent slope head fires in bean. Those crops consistently yielding near or in excess of 130 pounds included bean, wild hay, peas, oats, safflower, and cotton. Two of these crops, bean and oats, had also been among the highest in yields of particulates. Consistent yields of CO at near or less than 100 pounds were obtained from sorghum and all of the weeds. Fires from barley, rice, wheat, and tules had also been among those crops giving the lowest yields of particulate.

Use of back fires did not have the consistent effect of reducing CO emissions as was the general case with particulate matter. In fact in only three crops, barley, rice, and wheat, did back firing tend to reduce CO yield. Back fires at the 25 percent slope increased yield with the following crops: alfalfa, asparagus, bean, hay, peas, and sorghum. These results are in general agreement with those of the earlier project (2) wherein the statistical treatment of a large number of rice fires showed that no significant difference could be detected in CO emissions between head and back fires.

AS with the particulates from orchard crop fires, the yield of CO was considerably less than from field crops as shown in the averages presented earlier (about 56 pounds versus, 114 pounds). However, avocado again had the highest emissions, the yield being about 126 and 106 pounds with the higher and lower moisture levels, respectively. Whereas, the particulate yield from olive, the second evergreen species, had been nearly as low as from most other orchard crops, the CO yields were considerably higher, being about 106 and 140 pounds from the high and low moisture levels, respectively.

Again, when comparing the 11 deciduous orchard crops, the yield of CO was not significantly reduced when the fuels in either cold or roll-on fires had been further dried to about the 25 percent moisture level (dwb). Within a given moisture level, however, emissions from roll-on fires were increased (41.4 versus 54.9 pounds at higher moisture and 34.7 versus 49.9 pounds at lower moisture) and the increase was significant at the 99 percent confidence level. Thus, the practice of rolling piles onto existing fires does cause a real change in CO emissions, but the absolute amounts involved are relatively low when compared with many other crop plants. A decision whether to discourage roll-on type of ignition would depend upon the significance of CO relative to other pollutants in a given area, such as a chiefly urban area versus a chiefly rural one.

For avocado and olive it is obvious that the fuels should be dried to some level below 25 percent moisture (dwb) to ensure a reduction in CO comparable to that already achieved with the orchard crops; however, experiments were not conducted to determine what this moisture level might be.

Hydrocarbons: -- It was noted in the section on Facilities that two hydrocarbon analysers were used in this study. A newer model (Beckman 400) was found to be more sensitive than the older model being used and was substituted for it for the major portion of the project. Both instruments were used on 19 fires which permitted a correlation in the hydrocarbon yield data to be established (see Fig. 1). In discussing the results on hydrocarbon emissions in Table 1, only information from the newer instrument (HC #2) is used. Where this instrument was not available for earlier fires, yields have been calculated using the data in Fig. 1 and inserted between parentheses in the appropriate column of Table 1.

Fires from asparagus, bean, corn, hay, oats, and safflower, generally yielded more than 15 pounds of hydrocarbon per ton of fuel burned and alfalfa and pea fires yielded more than 30 pounds. With the exception of somewhat more than 20 pounds being emitted from 25 percent slope head fires of barley and wheat, these two crops, as well as rice, sorghum, mixed weeds, and tules, yielded near or below 10 pounds. Exceptionally low yields of about 1.7 pounds were obtained from tule fires.

It will be noted that alfalfa, bean, hay, oats, and peas were again among those crops with the higher levels of hydrocarbon as they had been with particulates and CO; barley, rice, wheat, and tules were again among the plants emitting the lower levels of the three pollutants.

As had been the case with CO, the use of back fires did not always result in reduction of hydrocarbon yields. This is in agreement with results of the earlier project (2).

It was noted in the averages presented earlier that orchard crops yielded less hydrocarbon (about 9 pounds per ton of fuel burned) than did field crops (about 17 pounds). But within the orchard group, hydrocarbon emissions from all avocado and all olive fires were considerably higher (32.0 and 17.4 pounds, respectively) than from all fires of the 11 other orchard crops (6.7 pounds).

Hydrocarbon yields for the 11 deciduous orchard crops were 5.9 and 9.7 pounds, respectively, for cold and roll-on fires at the higher moisture level, and 4.0 and 6.6 pounds, respectively, for the two fire types at the lower moisture level. The reduction in yield in each fire type due to moisture was significant at the 95 percent confidence level, as was the increase in yield from cold to roll-on at each moisture level. But it is evident that, as with yields of particulate and CO when those were significantly different, the absolute value changes were relatively small when compared with other crop plants.

Drying avocado and olive down to somewhat below the 25 percent moisture level would be necessary before hydrocarbon could be reduced to levels comparable with other orchard species.

Particle Size Distribution

The distribution of the particle sizes was determined in at least one fire for 30 of the 31 crop plants burned; mixed weeds were deleted from this portion of the study. In most cases particulate samples were taken from each burning condition within a given crop. If more than one fire was sampled for a given burning condition, the results were averaged. Mass median diameter (MMD) and percent of particles less than 1 and 2 microns are given in Table 2. The particle diameters plotted against cumulative mass percent less than the indicated particle diameter are included as pages 53 through 76 at the end of this section and in the same order as presented in Table 2.

The great majority of particles from the 99 fires sampled were sub-micron in size. In 87 of these samples, the MMD was .20 microns or less. The MMD of two of the remaining samples was .43 and .64 microns (oats, 25 percent head fire and nectarine, roll-on at high moisture, respectively) while the particle sizes of the rest of the fires fell between .21 and .28 microns. The MMD of all field crop fires, including weeds, and of all orchard crop fires, including vines, both averaged .13 microns.

When head and back fires of field crops at the 25 percent slope were compared, it was found that the average MMD was .22 and .11 microns; this difference was significant at the 99 percent confidence level.

Drying the orchard fuels down from the higher to the lower moisture level tended to reduce particle size but the differences were not significant. With cold ignition, the MMD's were .08 and 0.6 microns at the high and low moisture, respectively, and .18 and .14 microns with the roll-on fires at the two moisture levels. However, within either moisture level, roll-on fires increased particle size significantly. At the higher moisture, the increase (.08 to .18 microns) was significant at the 95 percent confidence level, and at the lower moisture the increase (.06 to .14 microns) was significant at the 99.9 percent confidence level.

Table 2. Particle Mass Median Diameter and Percent of Particles Less Than 1μ and 2μ from Burning Residues from Various Field, Vine and Orchard Crops, and Weeds.

Crop	Type of fire	% Moisture dry wt. basis	Mass median diameter, microns	Percent of particles less than 1μ	Percent of particles less than 2μ
Field Crops					
Alfalfa	H-25[a]	10.4	.21	89	97
	B-25	10.4	.15	91	97
Asparagus fern (baled)	H-25	10.5	.14	91	96
	B-25	10.5	.06	94	97
Barley	H-15	8.0	.05	93	97
	B-15	7.5	.03	96	98
	H-25	8.1	.01	96	98
	B-25	10.0	--[b]	--	--
	Flat	9.6	.06	96	100
Bean (red)	H-15	12.1	.15	91	97
	B-15	11.8	.15	90	96
	H-25	11.0	.22	89	97
	B-25	11.7	.07	94	98
Corn	H-15	16.8	.18	85	93
	B-15	14.2	.12	87	94
	H-25	12.4	.11	92	97
	B-25	13.2	.07	92	96
Cotton	Windrow	6.2	.09	96	99
Wild Hay	H-25	10.4	.25	86	95
	B-25	10.1	.18	89	96

[a] H and B; Head and Back fires, respectively. 15 or 25 refers to percent of slope used.

[b] All particles collected on the 5th stage and back-up filter so that calculation of distribution curve was not possible.

Table 2. (continued)

Crop	Type of fire	% Moisture dry wt. basis	Mass median diameter, microns	Percent of particles less than 1μ	2μ
Oats	H-15	10.2	.06	85	90
	B-15	10.2	.09	91	96
	H-25	7.1	.43	83	96
	B-25	7.6	.18	90	97
	Flat	11.1	.09	90	96
Pea Vines	H-25	9.8	.19	91	97
	B-25	9.8	.11	92	97
Rice	H-15	10.1	.16	93	98
	B-15	11.7	.07	93	97
	H-25	9.4	--[b]	--	--
	B-25	10.2	.10	97	99
Safflower	H-15	13.9	.13	90	96
	B-15	15.3	.20	88	95
Sorgum	H-25	55.0	.13	87	94
	B-25	56.6	.10	89	95
Wheat	H-15	7.6	.10	84	90
	B-15	8.9	.05	90	95
	H-25	20.5	.26	86	95
	B-25	11.8	.06	93	97
	Flat	9.4	.05	88	92
<u>Vine Crops</u>					
Boysenberry	Pile	3.9	.03	96	98
Grape	Cold	40.7	.11	87	93
	Roll-on	37.5	.22	85	94
	Cold	24.0	.04	93	97
	Roll-on	22.3	.04	96	98

Table 2. (continued)

Crop	Type of fire	% Moisture dry wt. basis		Mass median diameter, microns	Percent of particles less than 1μ	Percent of particles less than 2μ
Orchard Crops						
Almond	Cold	39.0		.08	92	96
	Roll-on	38.5		.08	93	97
	Cold	26.8		.07	91	95
	Roll-on	26.9		.13	90	96
Apple	Cold	30.9		.09	90	95
	Roll-on	34.5		.13	89	95
	Cold	20.7		.05	91	95
	Roll-on	20.7		.10	91	96
Apricot	Cold	39.2		.14	90	96
	Roll-on	41.1		.22	88	96
	Cold	25.4		.04	93	97
	Roll-on	28.8		.17	90	97
		lvs., twigs	branches			
Avocado	Cold	31.5	91.6	.15	92	98
	Roll-on	--	83.5	.26	88	97
	Cold	17.4	35.7	.14	92	97
	Roll-on	15.7	35.8	.16	91	97
Cherry	Cold	39.8		.08	93	97
	Roll-on	44.8		.07	91	96
	Cold	30.3		.07	91	95
	Roll-on	37.5		.11	93	97
		pinnae	petiole			
Date Palm	Pile	11.4	16.0	.19	84	92

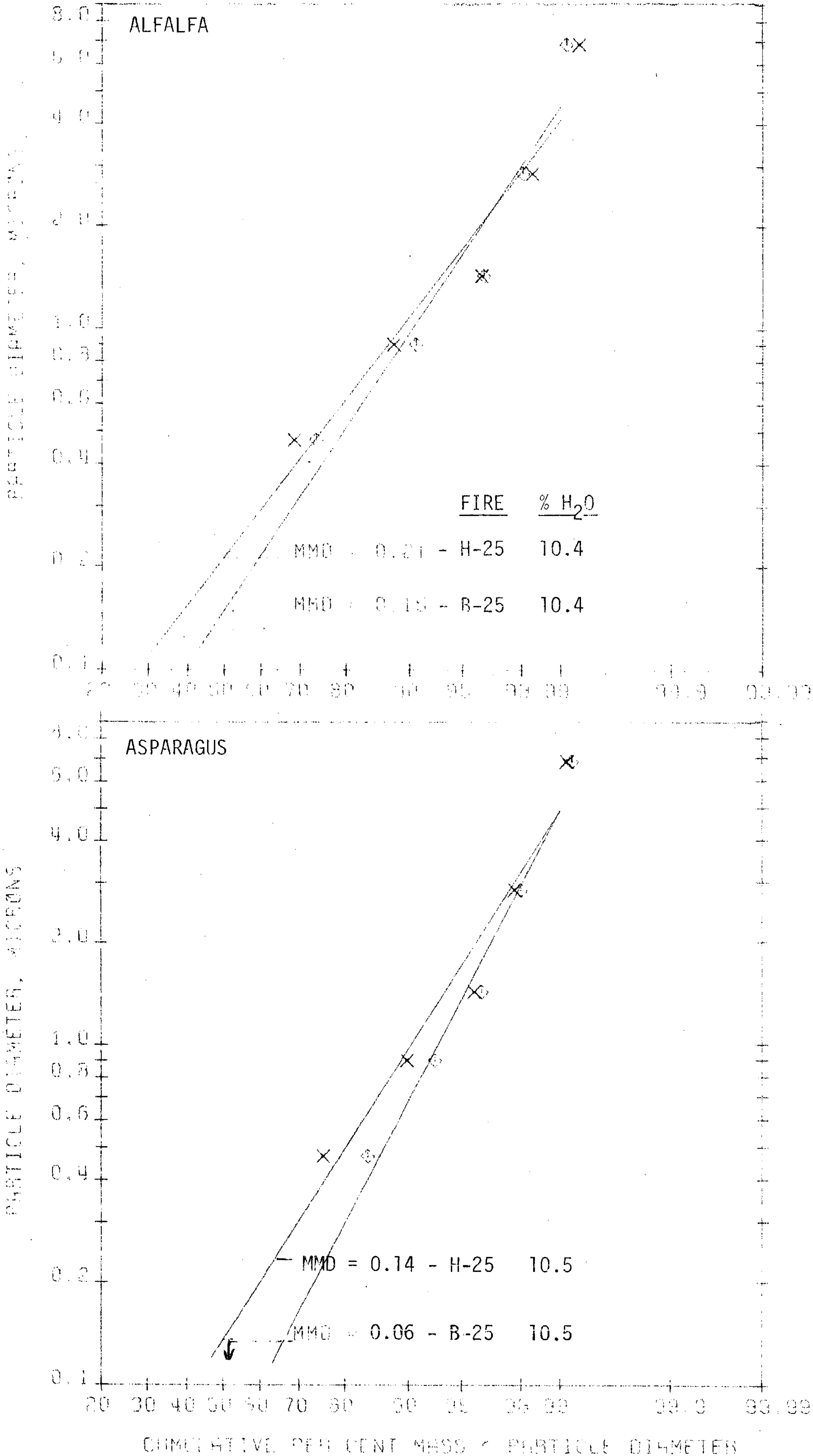
Table 2. (continued)

Crop	Type of fire	% Moisture dry wt. basis		Mass median diameter, microns	Percent of particles less than 1μ	2μ
Fig	Cold	39.7		.05	94	97
	Roll-on	40.9		.08	94	98
	Cold	20.7		.07	91	96
	Roll-on	20.8		.13	88	95
Nectarine	Cold	34.4		.01	91	94
	Roll-on	37.2		.64	59	72
	Cold	31.3		.04	90	94
	Roll-on	29.9		.11	89	95
		lvs., twigs	branches			
Olive	Cold	25.8	44.2	.08	93	97
	Roll-on	23.8	46.0	.25	87	96
	Cold	11.1	34.9	.03	94	97
	Roll-on	11.5	30.8	.28	83	93
Peach	Cold	43.1		.09	96	99
	Roll-on	44.6		.13	95	99
	Cold	24.3		.02	94	97
	Roll-on	25.8		.15	91	97
Pear	Cold	46.9		.08	90	95
	Roll-on	40.5		.15	91	97
	Cold	28.2		.12	92	97
	Roll-on	21.8		.23	87	95
Prune	Cold	28.0		.02	94	97
	Roll-on	31.1		.05	98	100
	Cold	19.8		.02	95	98
	Roll-on	20.8		.12	91	96

Table 2. (continued)

Crop	Type of fire	% Moisture dry wt. basis	Mass median diameter, microns	Percent of particles less than 1μ	Percent of particles less than 2μ
Walnut	Cold	42.7	.05	93	97
	Roll-on	46.6	.06	94	98
	Cold	31.5	.08	91	96
	Roll-on	34.6	.15	90	96
<u>Weeds</u>					
Ditch Bank	H-25	11.1	.28	86	96
	B-25	11.1	.19	89	96
	Pile	13.8	.68	63	81
Tule	Pile	17.4	.06	94	97
	Rack	15.6	.03	97	99

It is evident from these results that particles from agricultural fires are quite small and that the particle size distribution can be altered by manipulating the firing practice. It was shown earlier in this study, and also in part in a previous project (2), that back firing of field crops and the cold ignition of orchard crops minimized yield of particulates. These same techniques also reduce the size of the particles. But at the very small size involved, it is difficult, and perhaps outside of the scope of this project, to indicate whether the reduction in size is a benefit.


ALFALFA
FIRE
% H_2O
H-25
10.4
B-25
10.4
ASPARAGUS
MMD = 0.14 - H-25
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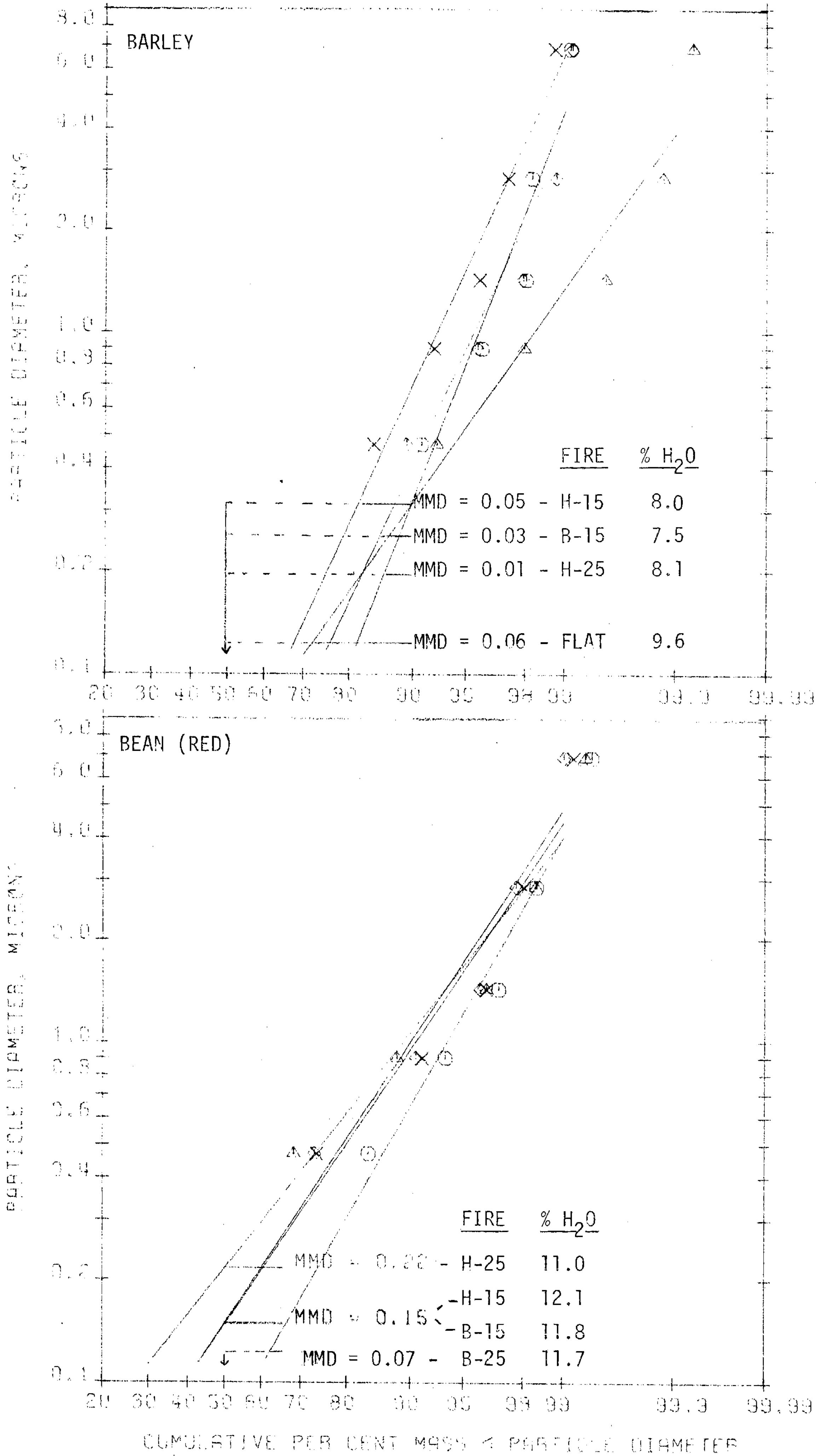
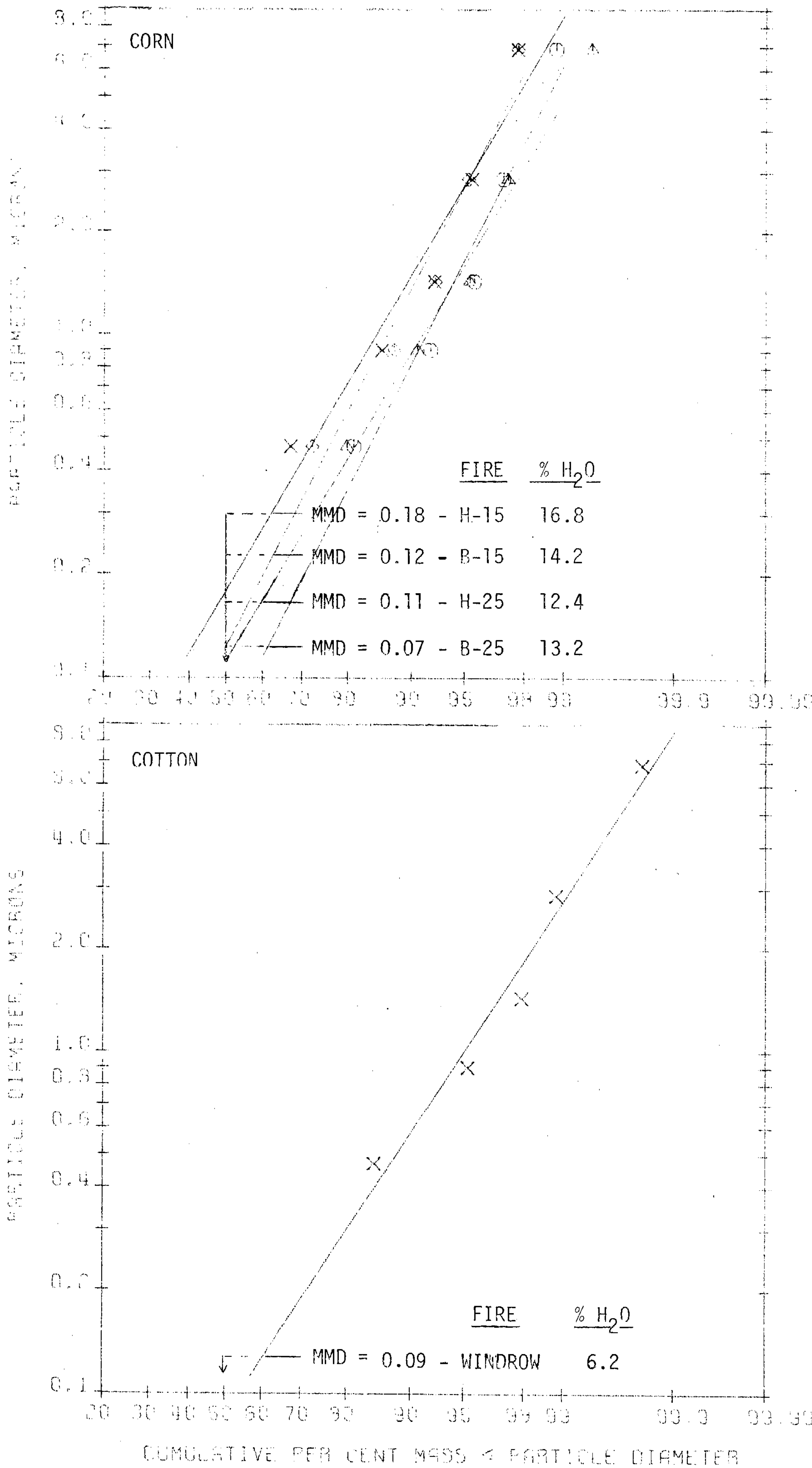
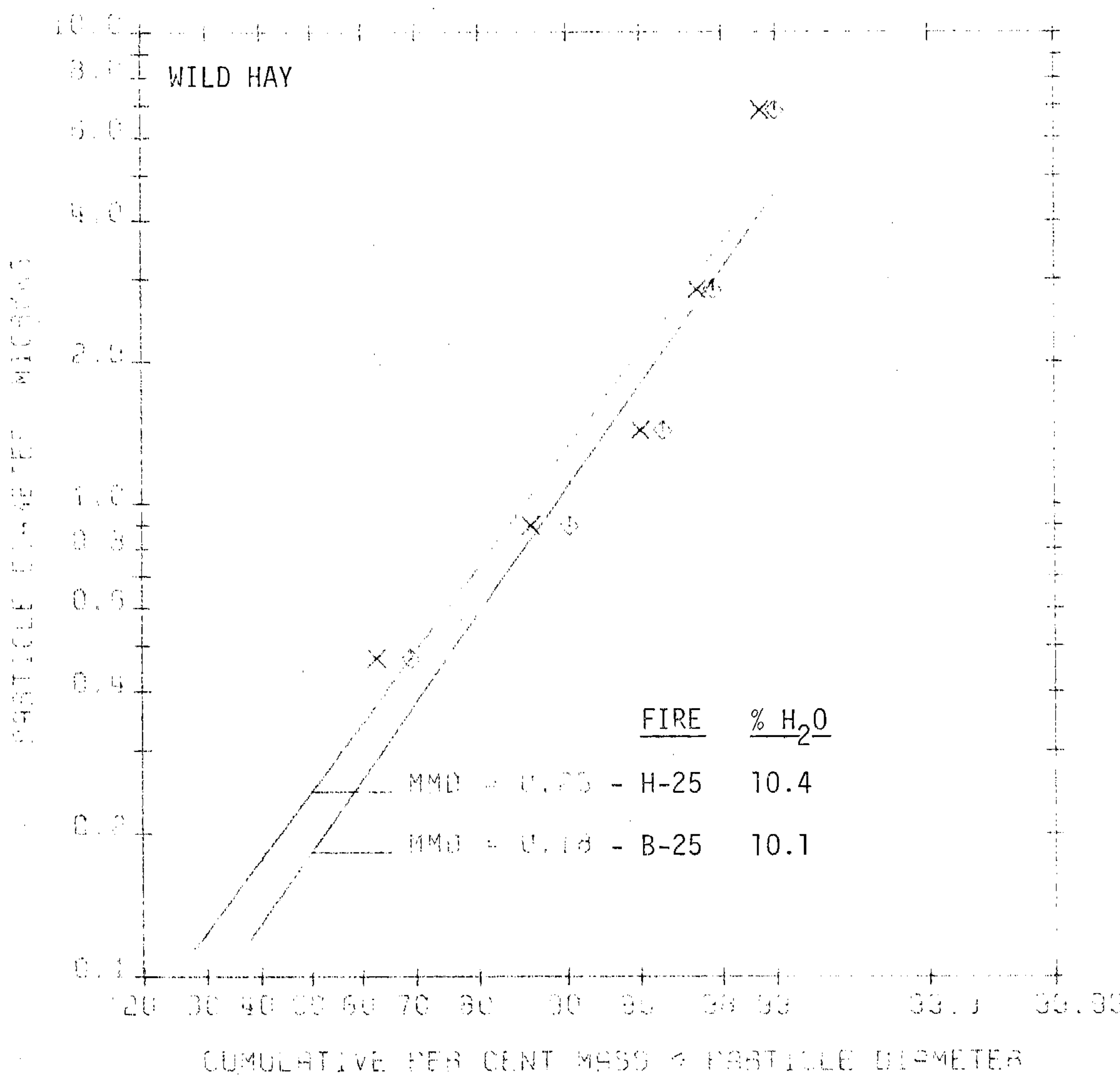
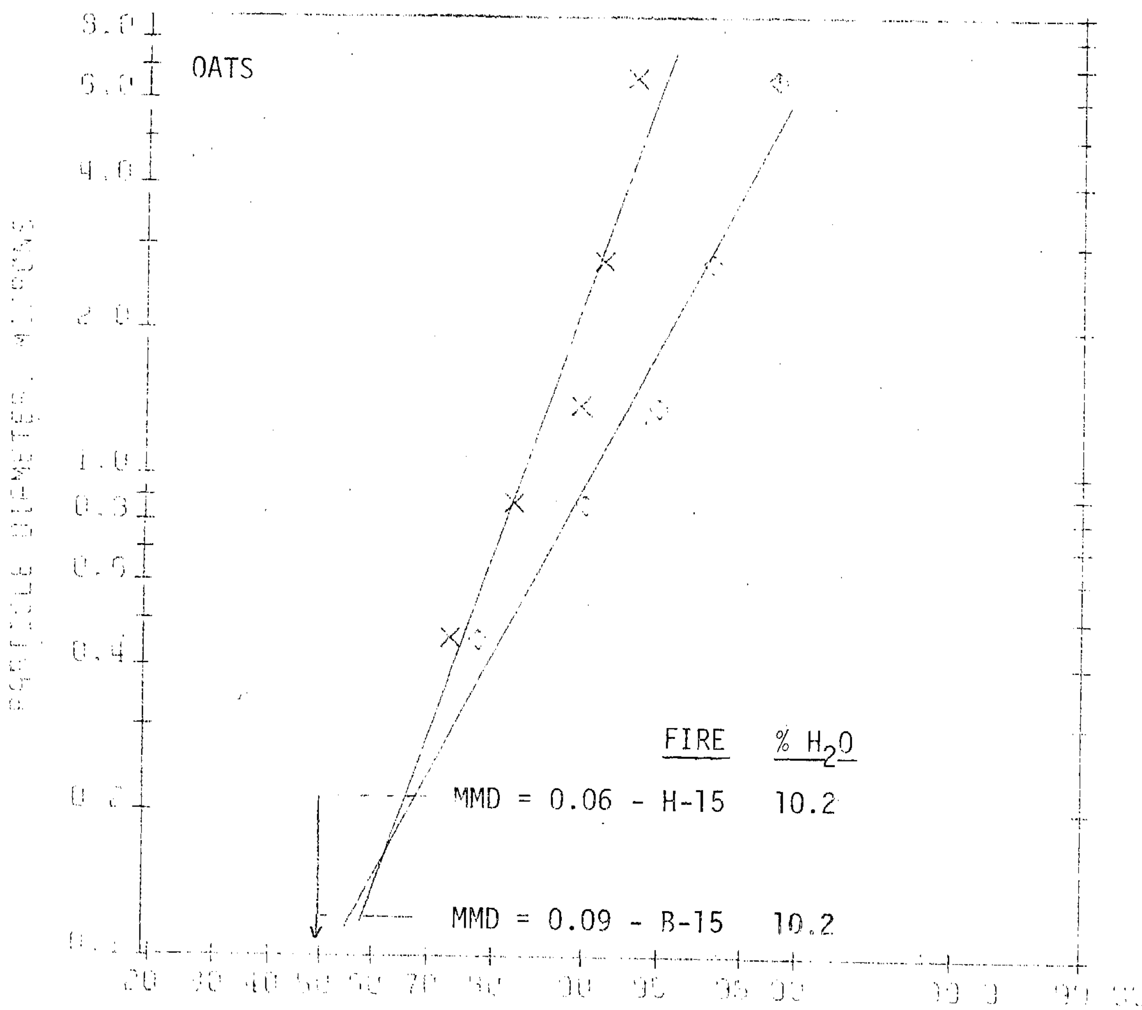
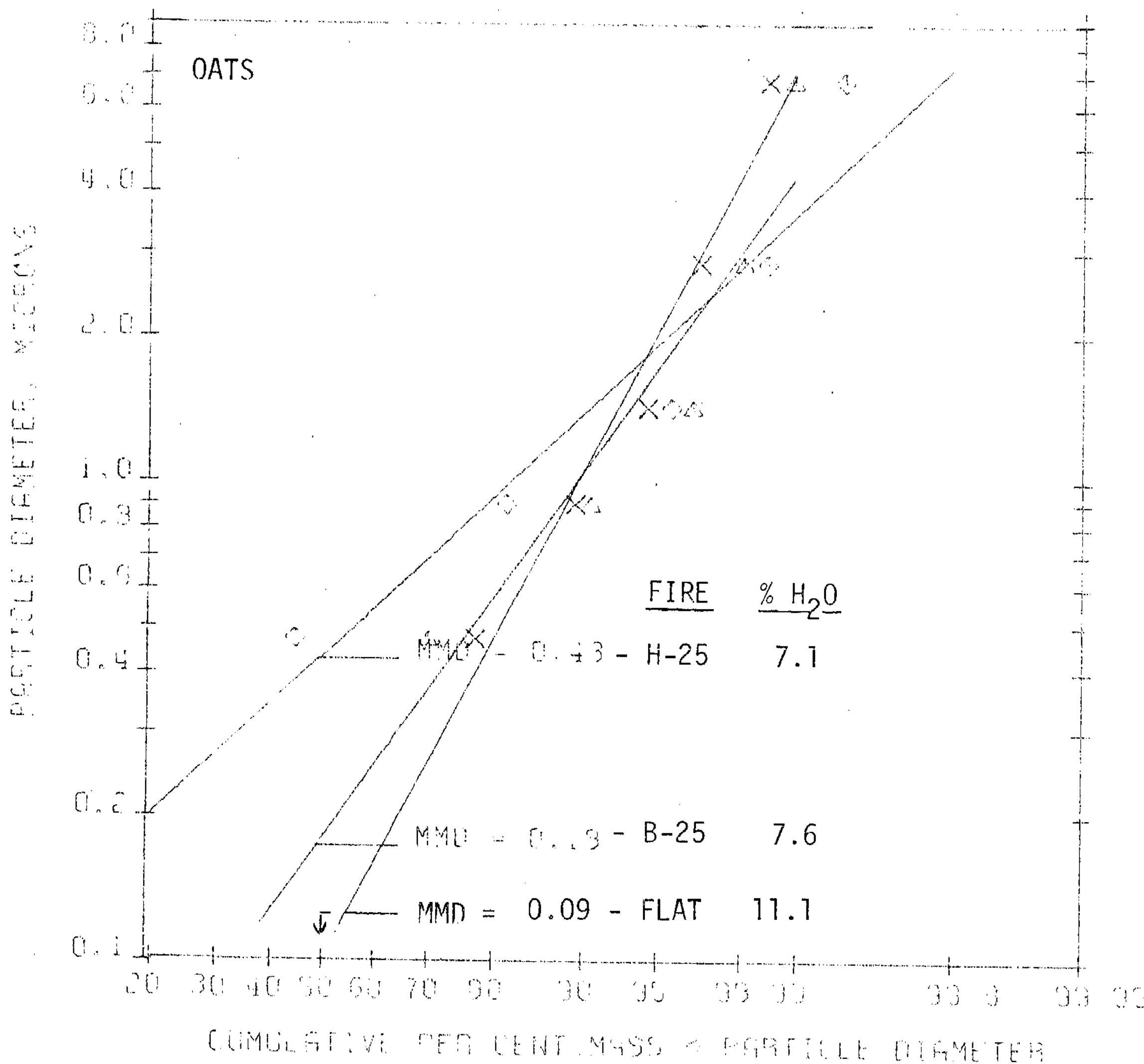
MMD = 0.06 - B-25
10.5
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

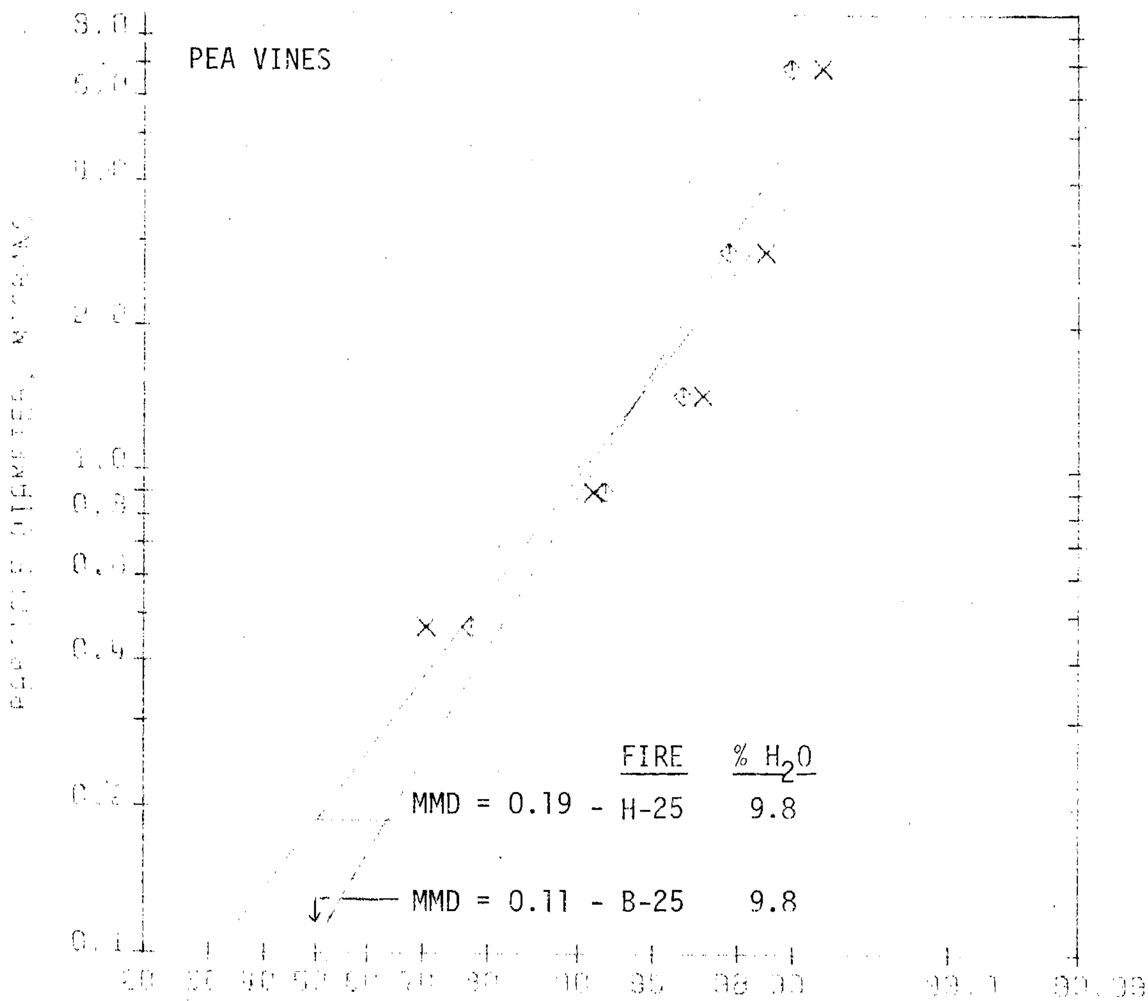

BARLEY
FIRE
% H_2O
MMD = 0.05 - H-15 8.0
MMD = 0.03 - B-15 7.5
MMD = 0.01 - H-25 8.1
MMD = 0.06 - FLAT 9.6
BEAN (RED)
FIRE
% H_2O
MMD = 0.22 - H-25 11.0
MMD ≈ 0.15 - H-15 12.1
- B-15 11.8
MMD = 0.07 - B-25 11.7
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

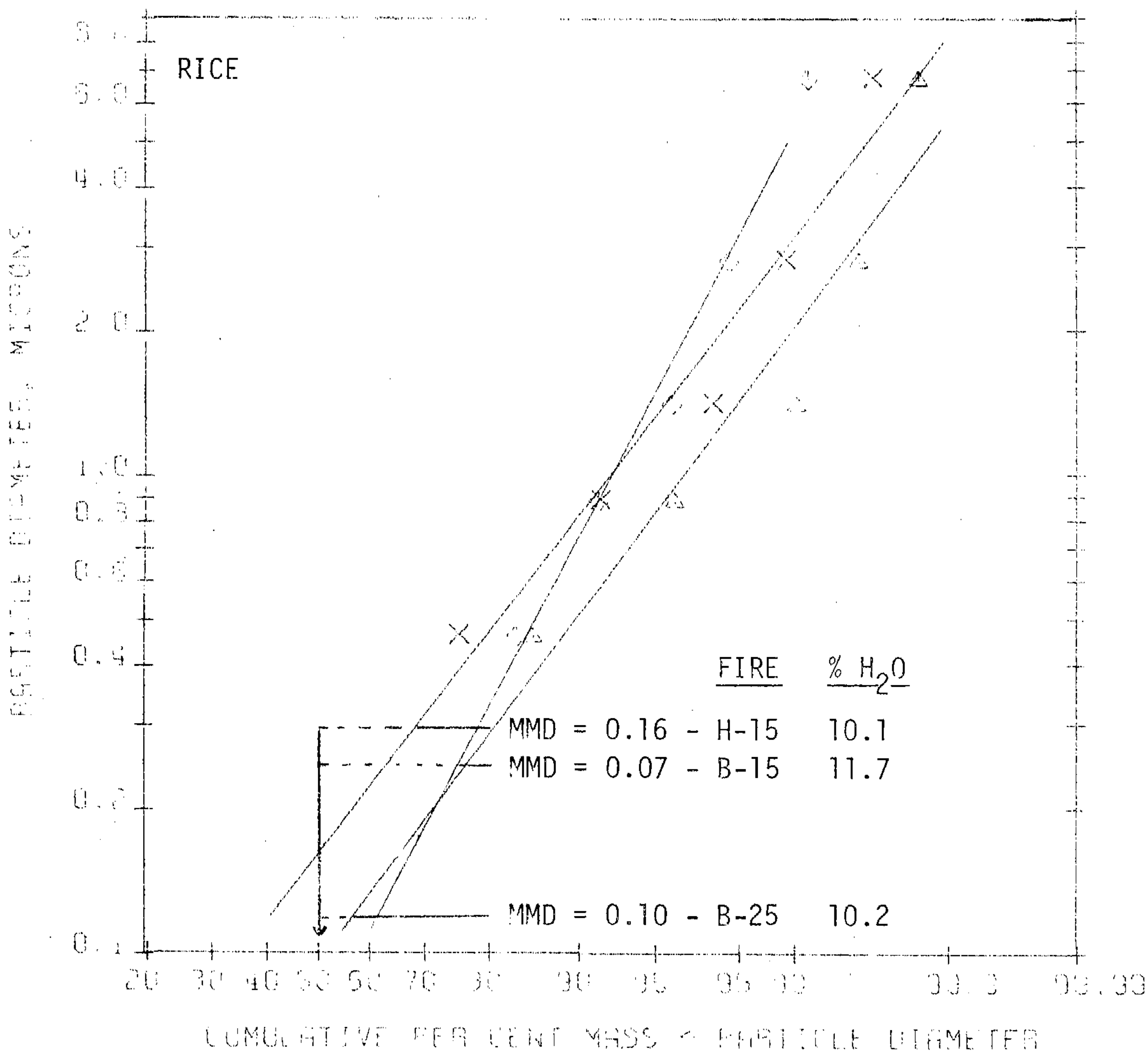

CORN
FIRE
% H_2O
MMD = 0.18 - H-15 16.8
MMD = 0.12 - B-15 14.2
MMD = 0.11 - H-25 12.4
MMD = 0.07 - B-25 13.2
COTTON
FIRE
% H_2O
MMD = 0.09 - WINDROW 6.2
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

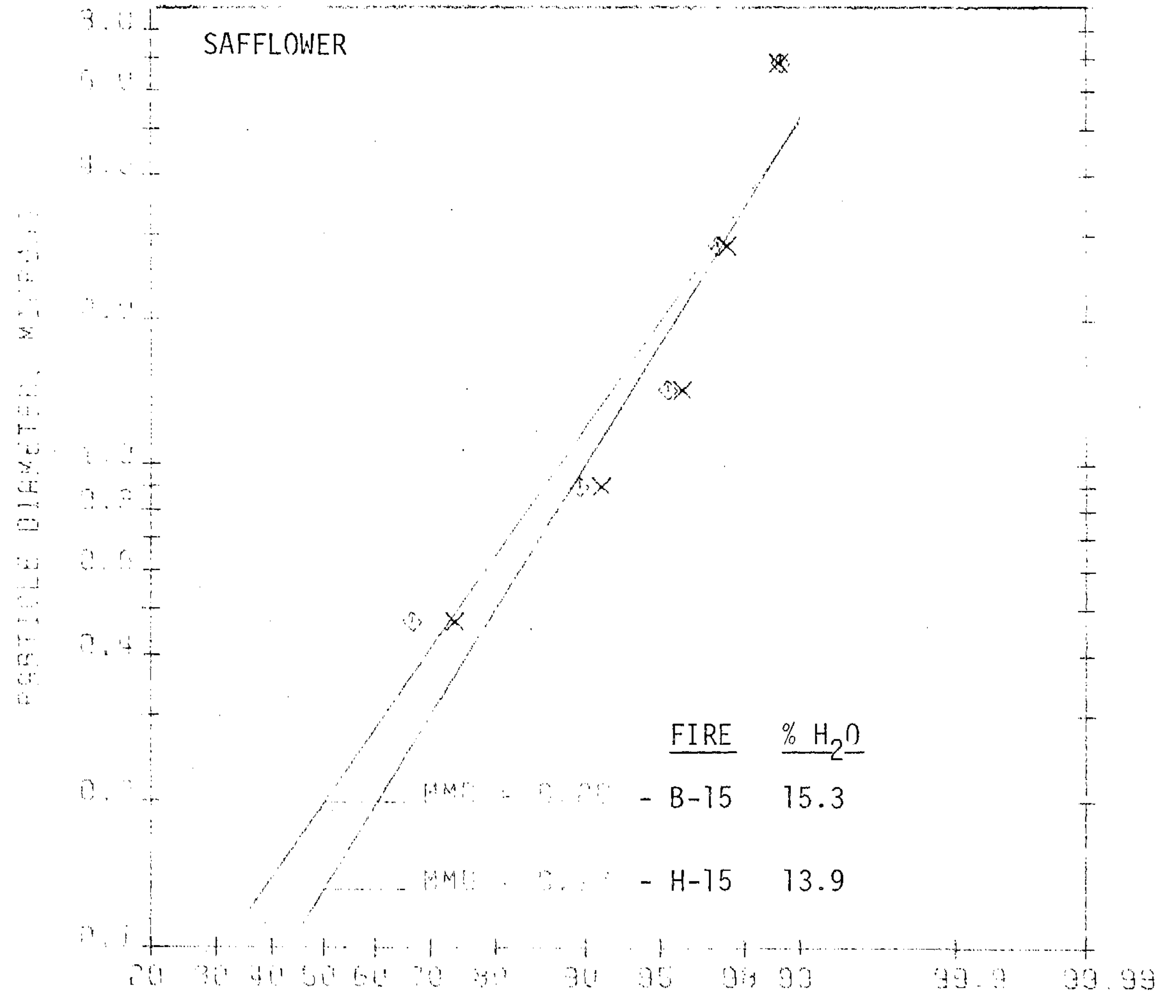

WILD HAY
FIRE % H_2O
MMD - H-25 10.4
MMD - B-25 10.1
CUMULATIVE PER CENT MASS

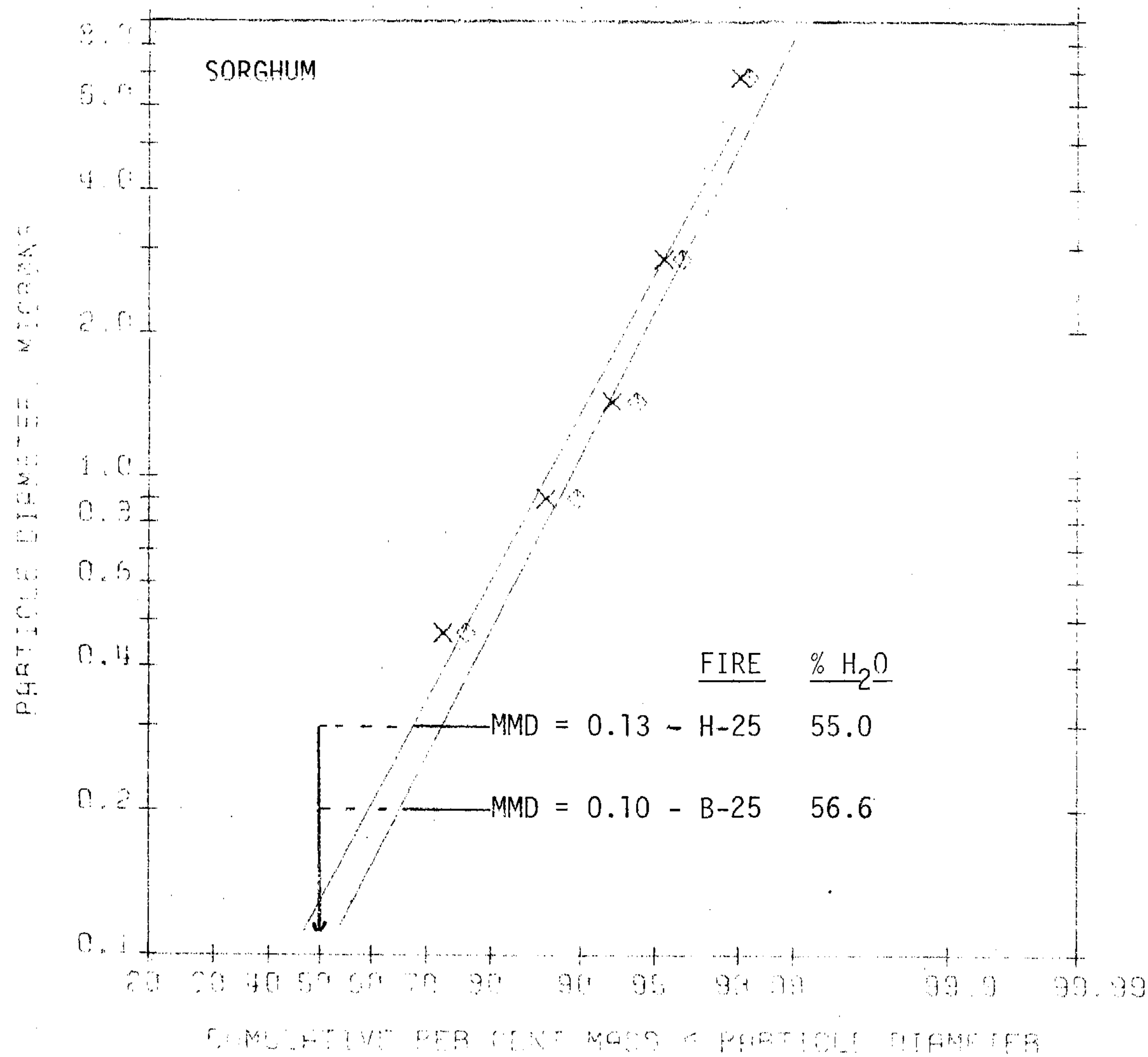

OATS
PARTICLE DIAMETER, MICRONS
FIRE % H_2O
MMD = 0.06 - H-15 10.2
MMD = 0.09 - B-15 10.2

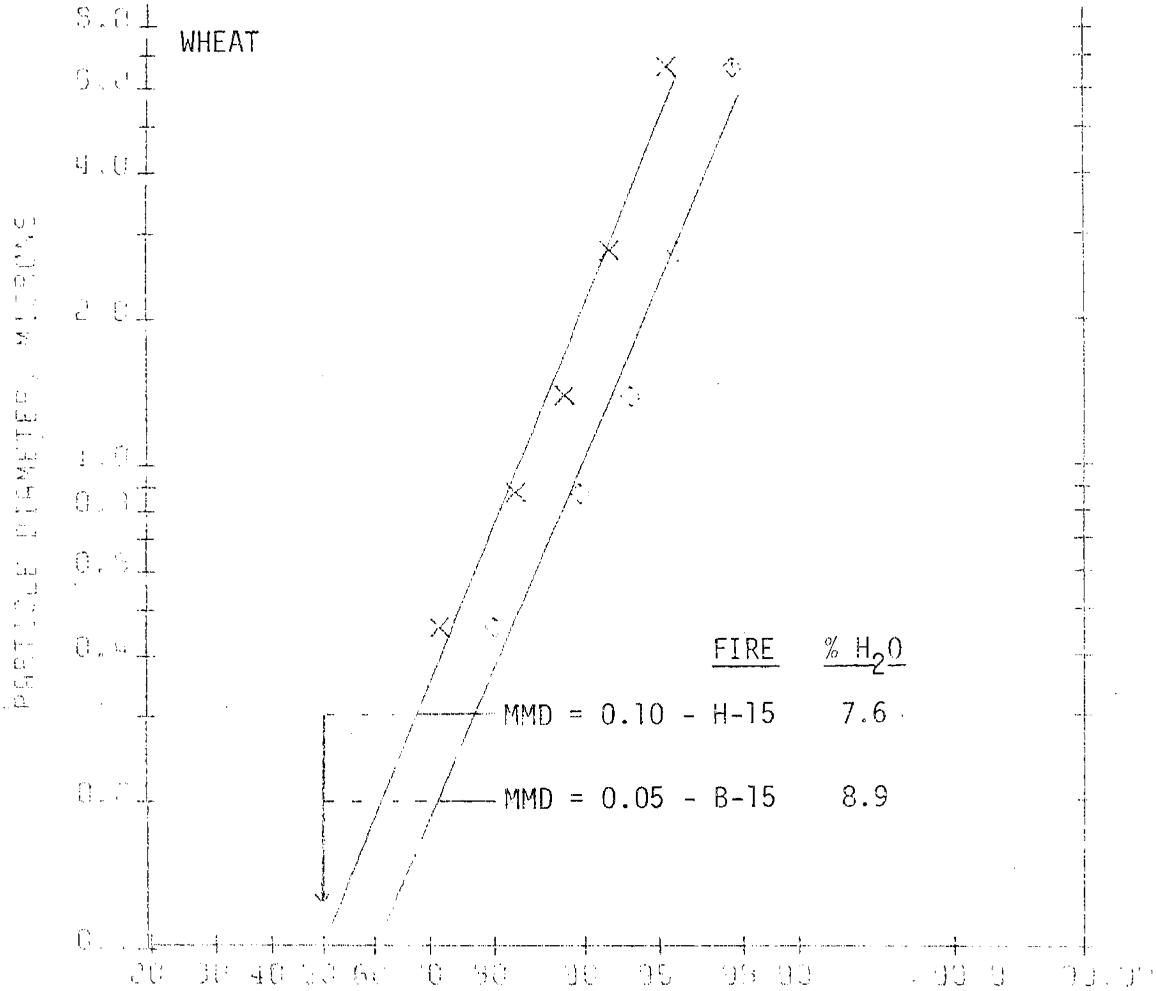

OATS
PARTICLE DIAMETER, MICRONS
FIRE % H_2O
- H-25 7.1
- B-25 7.6
MMD = 0.09 - FLAT 11.1
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

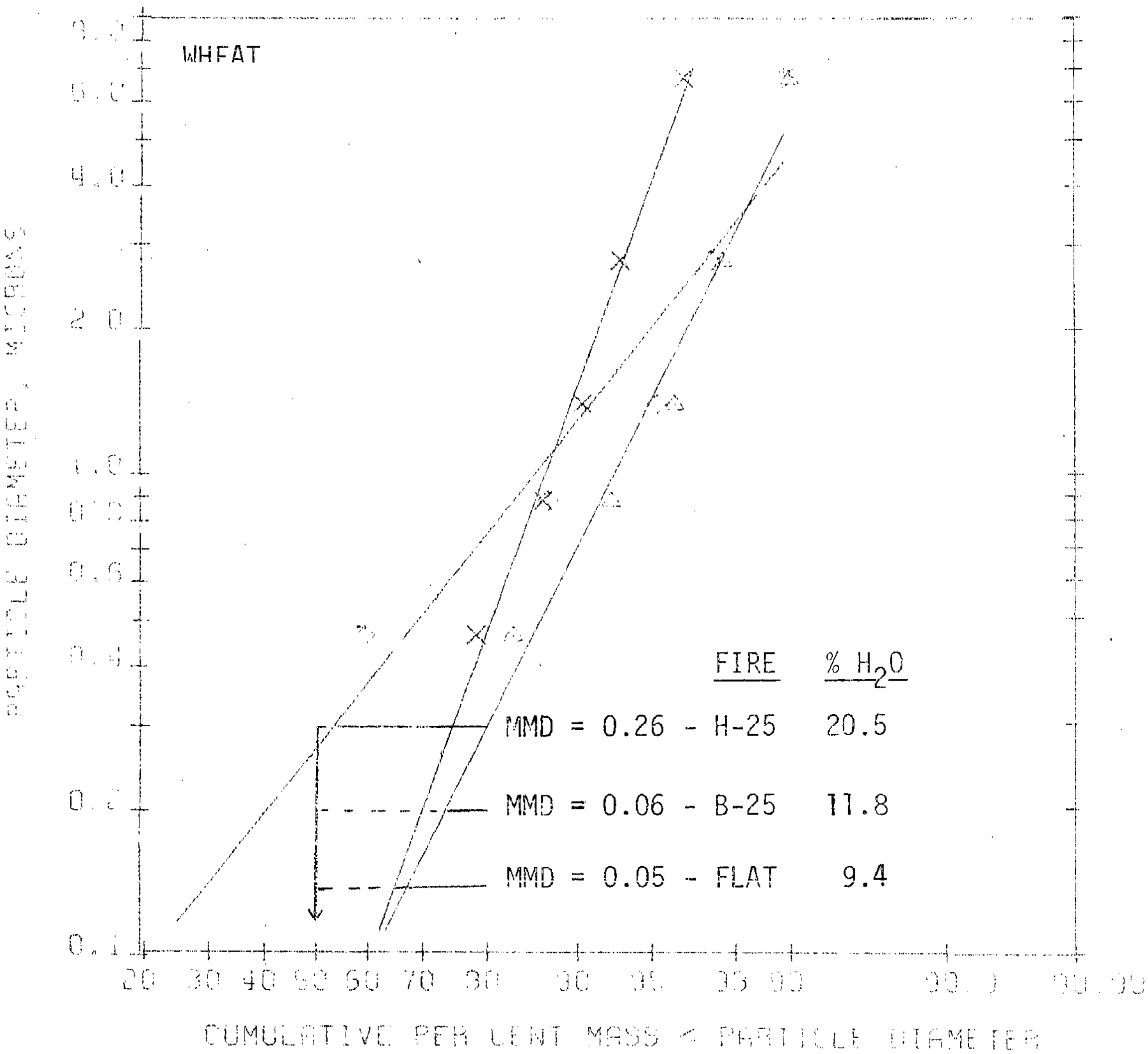

PEA VINES
FIRE % H_2O
MMD = 0.19 - H-25 9.8
MMD = 0.11 - B-25 9.8

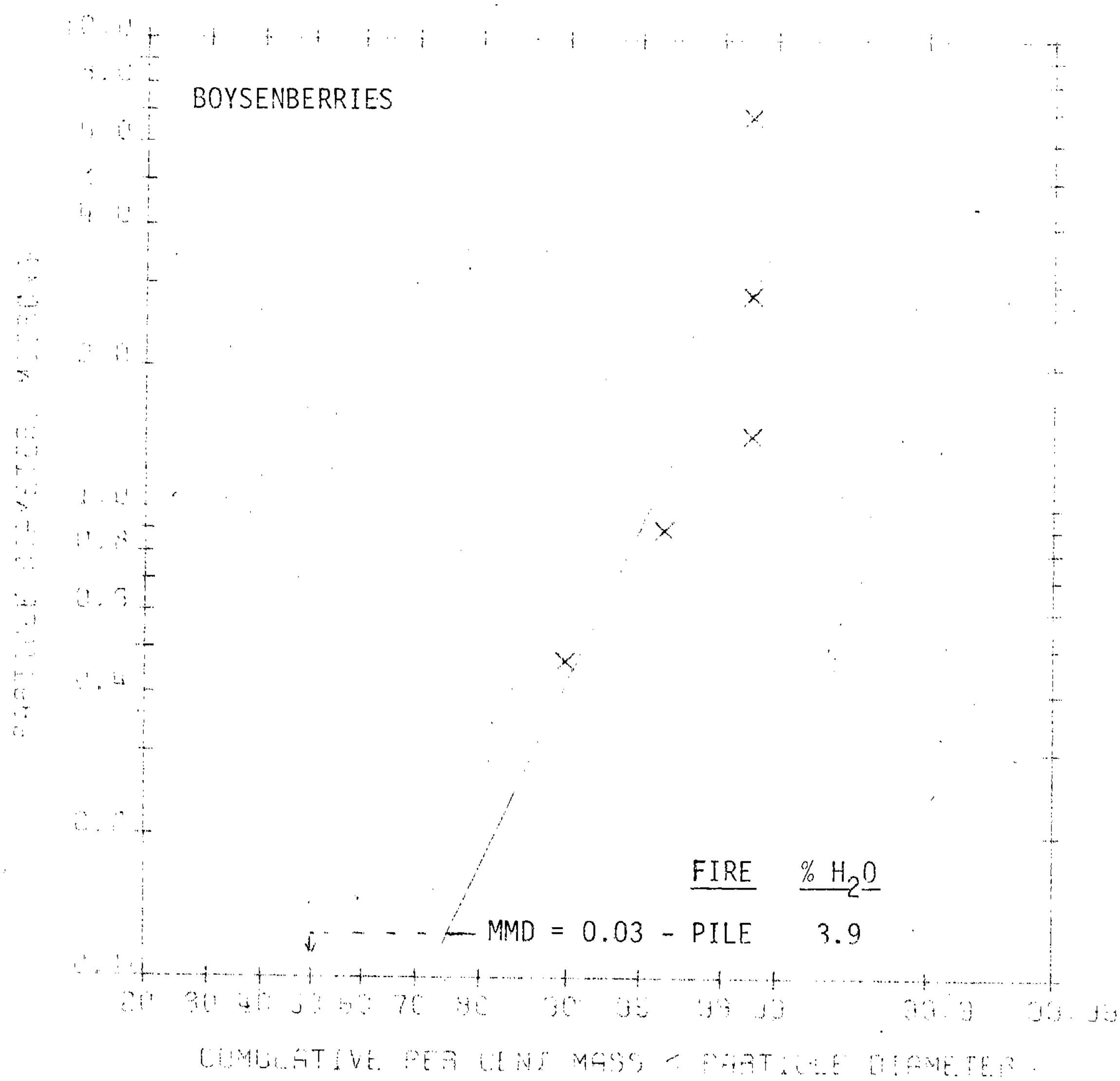

RICE
FIRE % H_2O
MMD = 0.16 - H-15 10.1
MMD = 0.07 - B-15 11.7
MMD = 0.10 - B-25 10.2

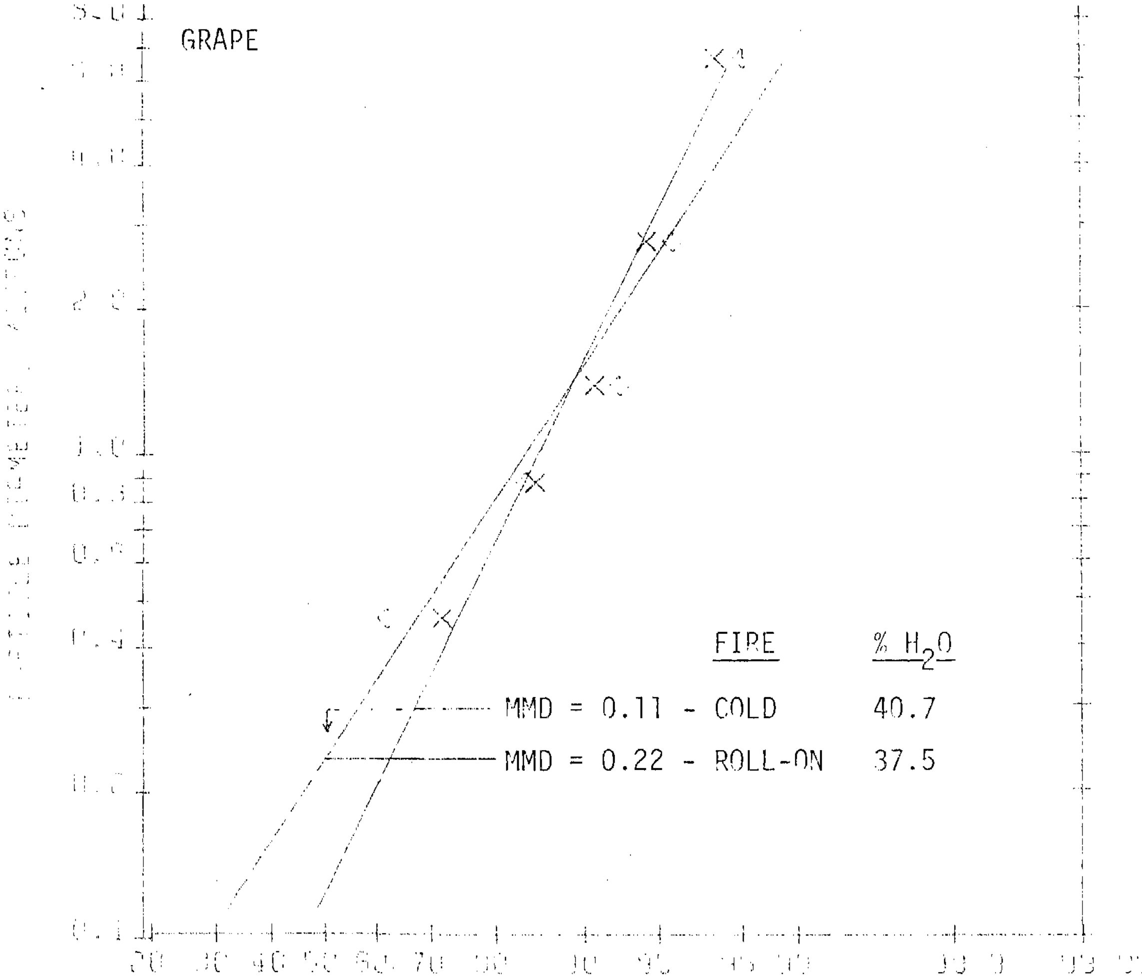

SAFFLOWER
FIRE
% H_2O
- B-15
15.3
- H-15
13.9

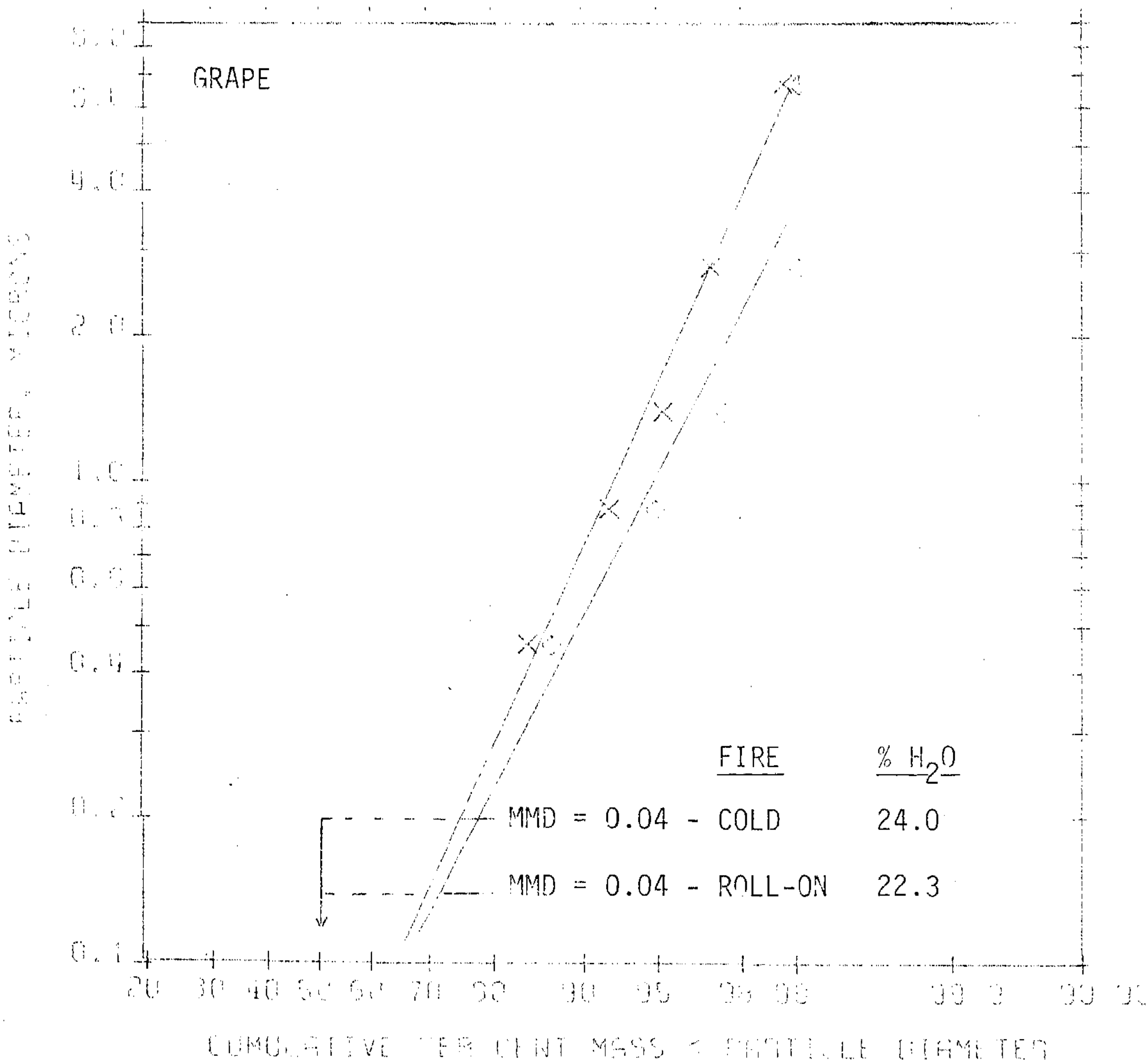

SORGHUM
FIRE
% H_2O
MMD = 0.13 - H-25
55.0
MMD = 0.10 - B-25
56.6
0.1
0.2
0.4
0.6
0.8
1.0
2.0
4.0
6.0

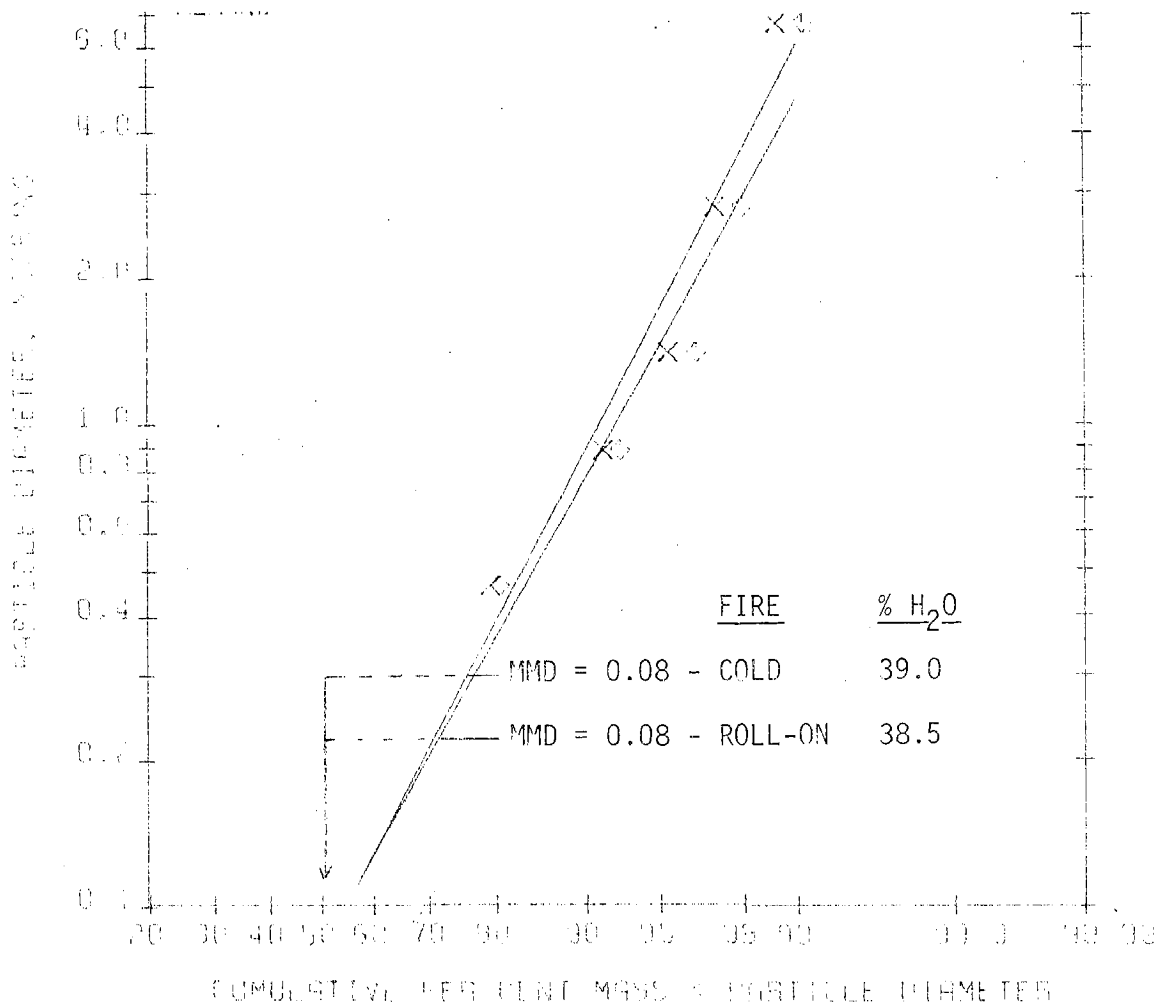

WHEAT
FIRE
% H_2O
MMD = 0.10 - H-15
7.6
MMD = 0.05 - B-15
8.9
PARTICLE DIAMETER, MICRONS


WHEAT
FIRE
% H_2O
MMD = 0.26 - H-25
20.5
MMD = 0.06 - B-25
11.8
MMD = 0.05 - FLAT
9.4
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


BOYSENBERRIES
FIRE
% H_2O
MMD = 0.03 - PILE
3.9
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


GRAPE
FIRE
% H_2O
MMD = 0.11 - COLD
40.7
MMD = 0.22 - ROLL-ON
37.5


GRAPE
FIRE
% H_2O
MMD = 0.04 - COLD
24.0
MMD = 0.04 - ROLL-ON
22.3
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


FIRE
% H_2O
MMD = 0.08 - COLD
39.0
MMD = 0.08 - ROLL-ON
38.5

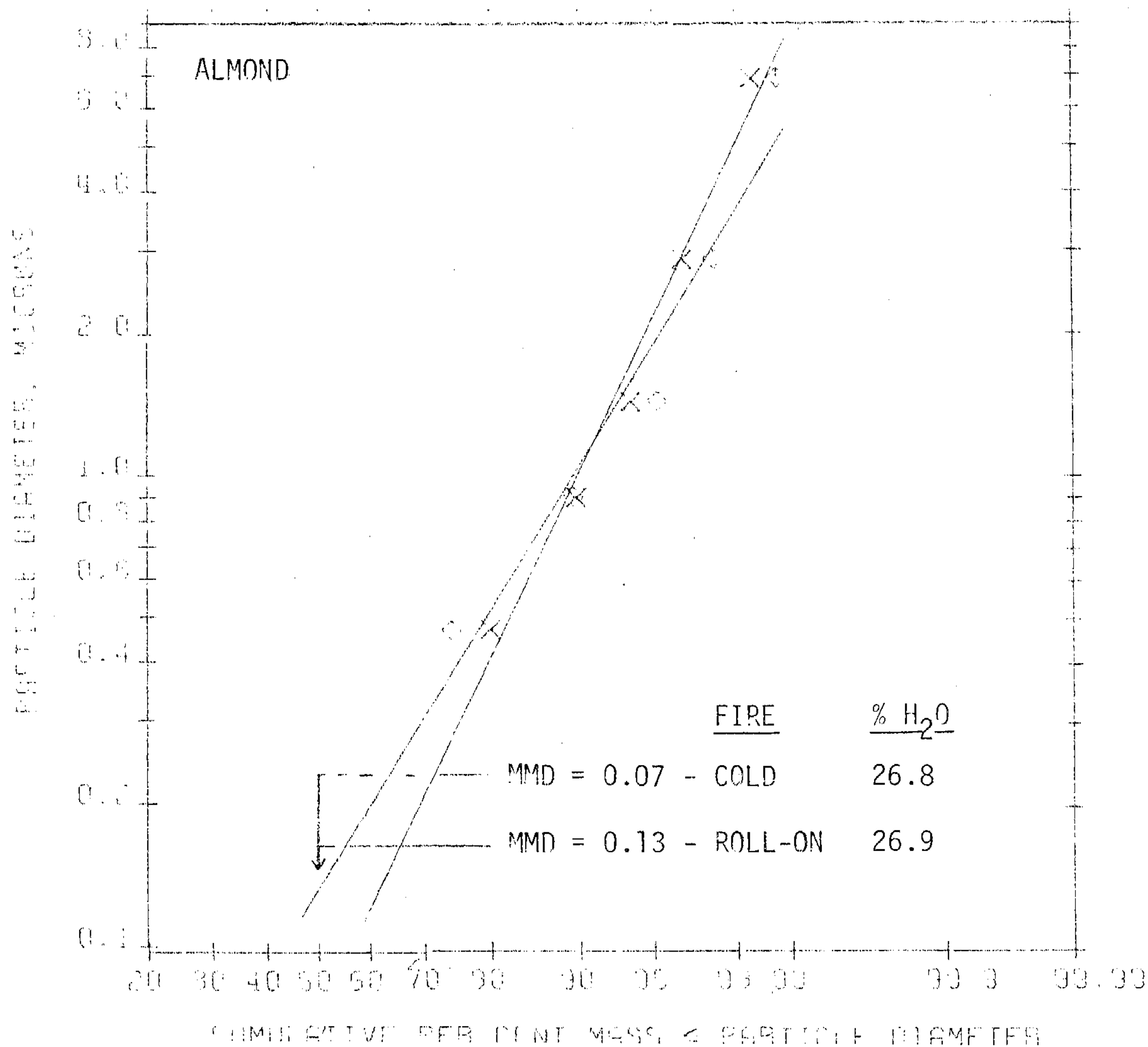
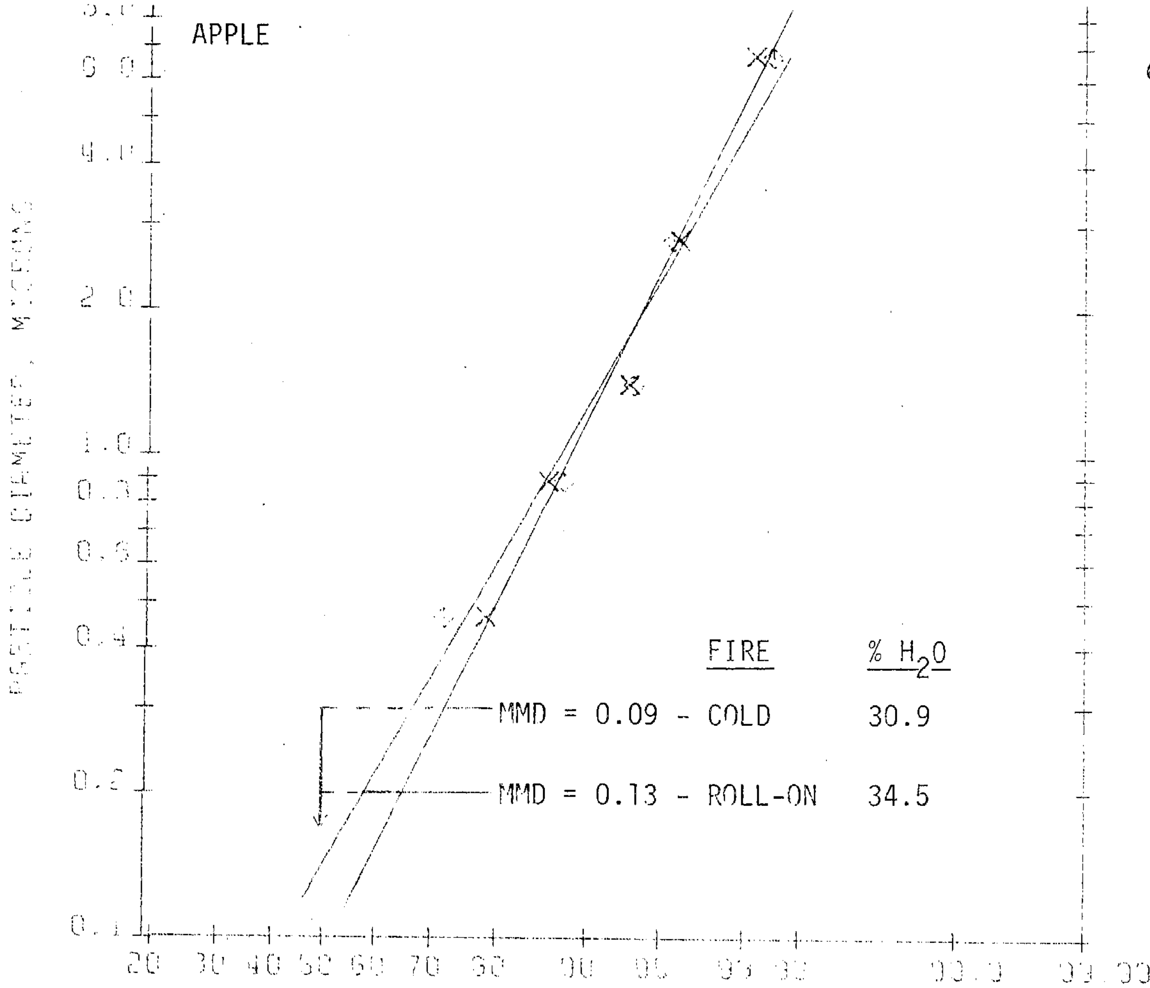
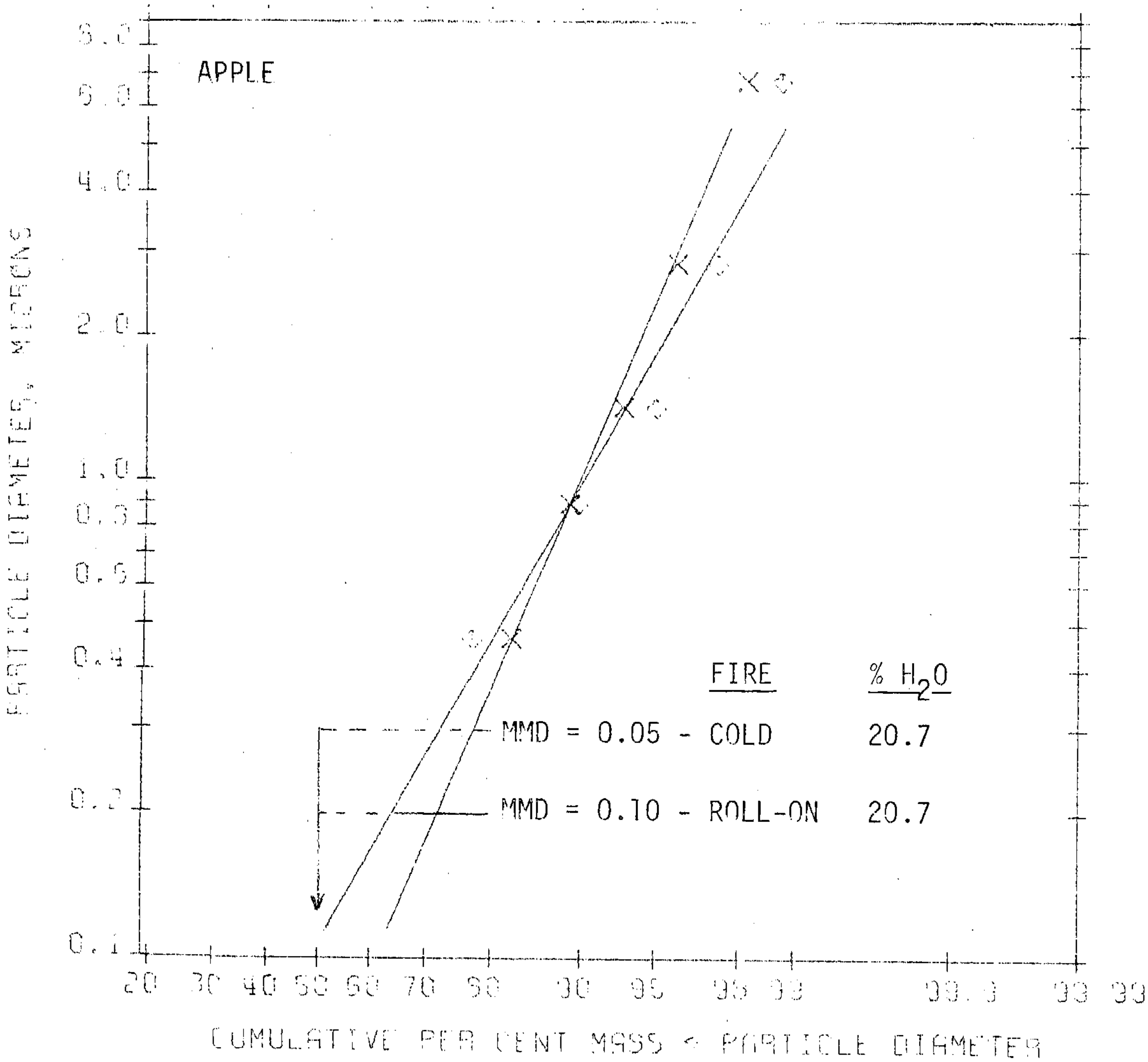
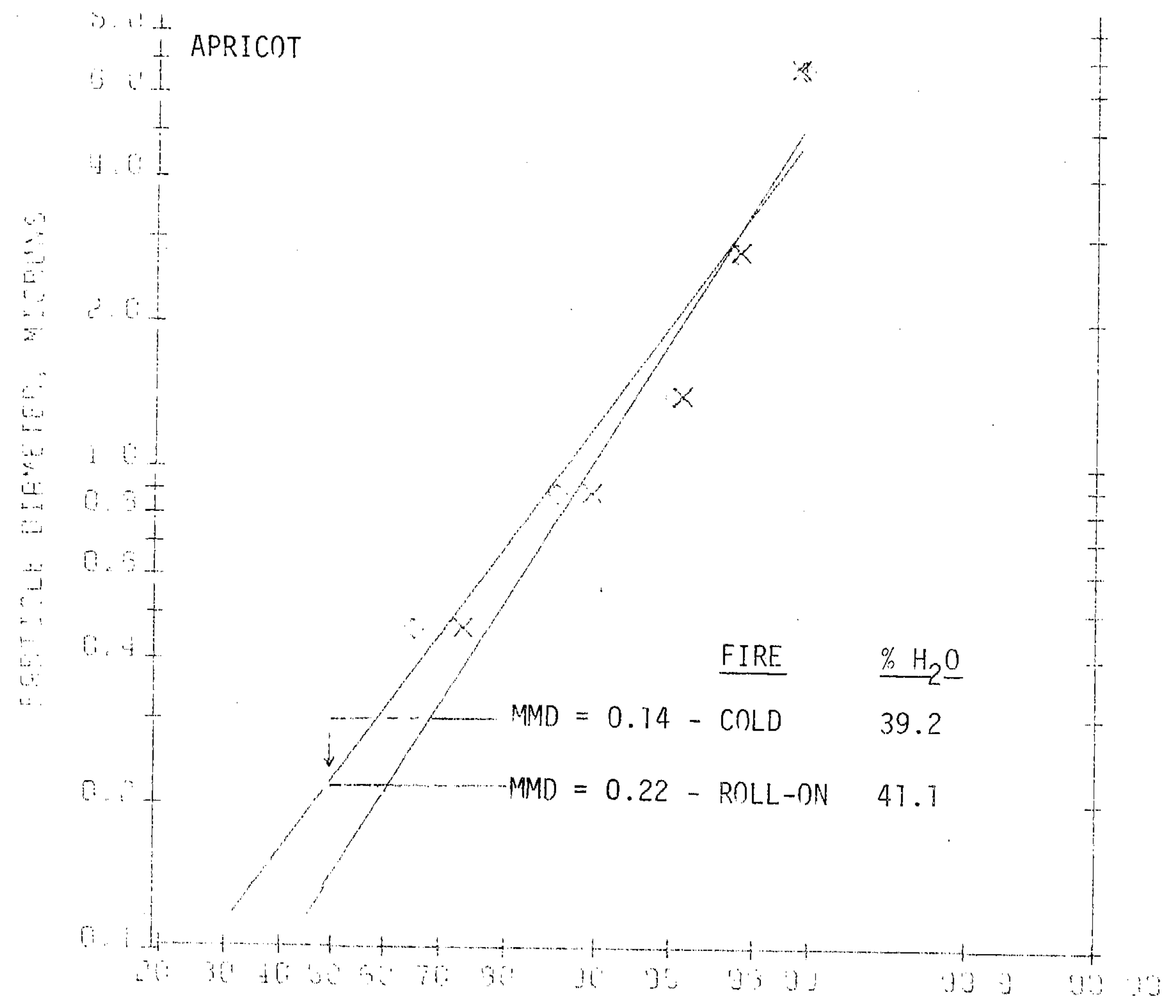

ALMOND
FIRE
% H_2O
MMD = 0.07 - COLD
26.8
MMD = 0.13 - ROLL-ON
26.9

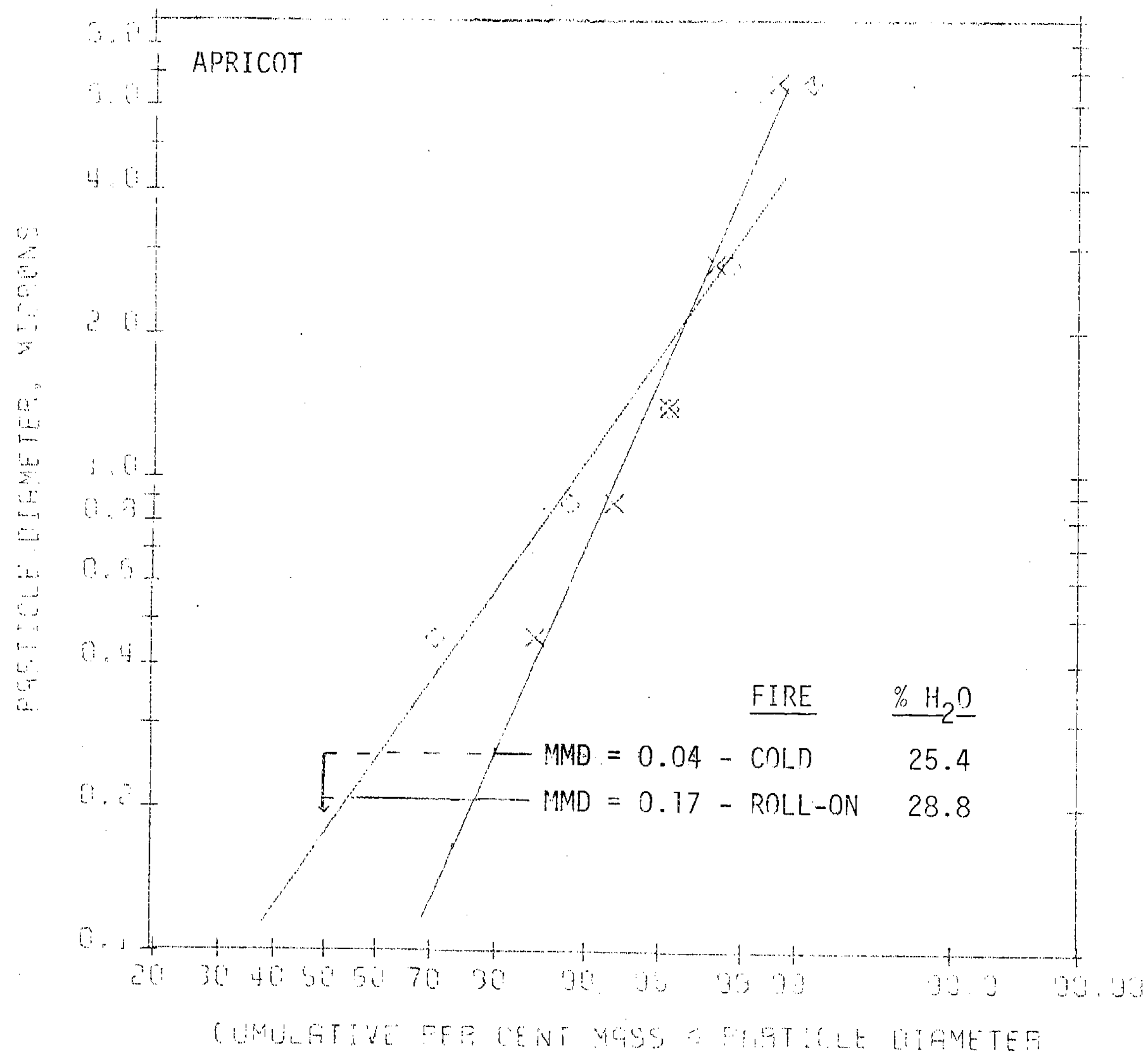
Table 1. (Continued)

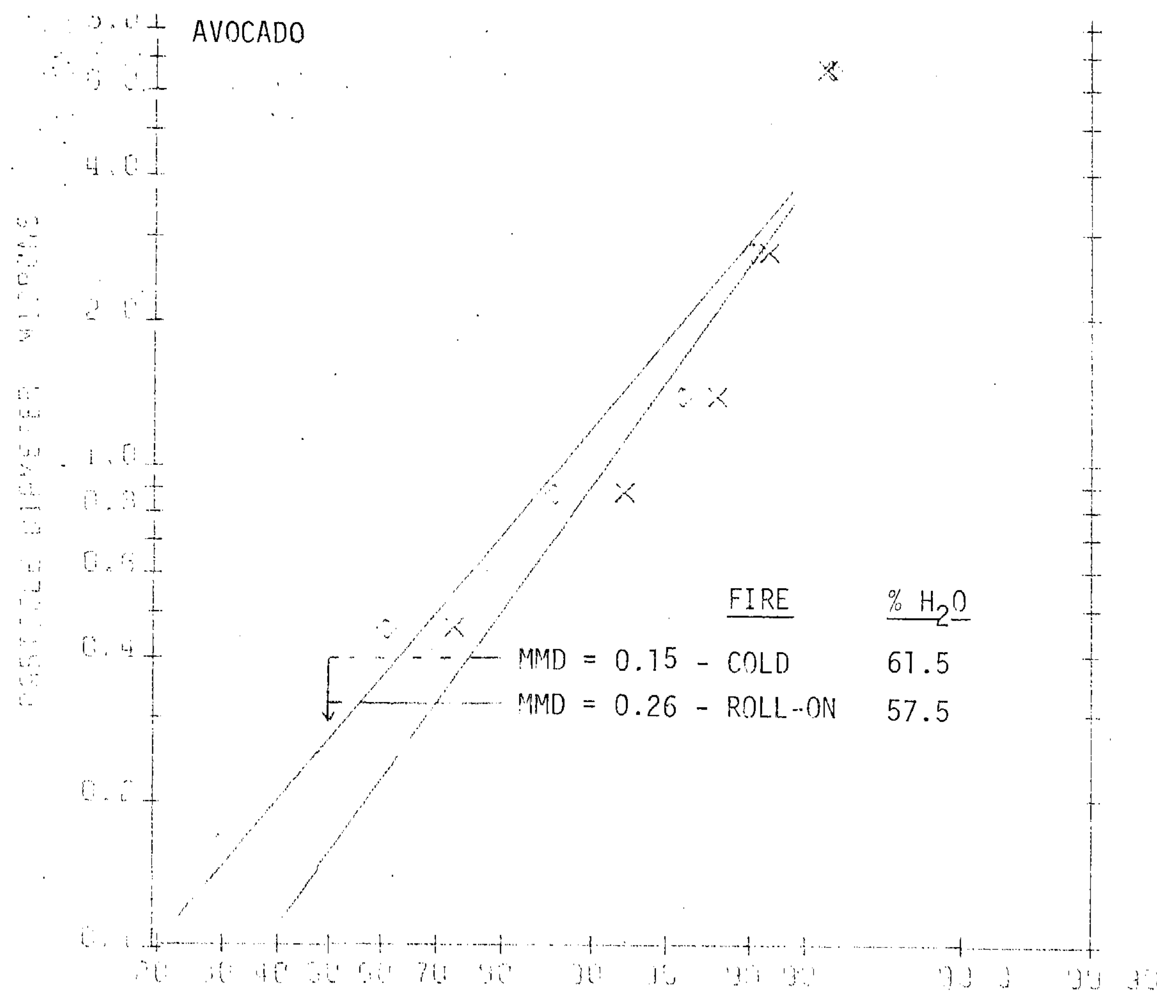
Crop	Type of Fire	% Moisture, dry wt. basis	Emissions, lbs. per ton fuel burned			
			Part.	CO	HC#1	HC#2
Pear	Cold	46.7	9.2[b]	47.2	...	7.6
	Roll-on	43.1	10.1	65.7	...	11.3
	Cold	...	8.8	47.4	...	5.1
	Roll-on	41.5	12.9[b]	67.1	...	10.7
	Cold	47.0	18.9[b]	63.8	...	10.7
	Roll-on	48.6	17.2	72.2	...	15.2
	Cold	40.6	...	55.3	...	7.9
	Roll-on	39.5	...[b]	61.8	...	12.9
	Cold	av. [43.9]	12.3	53.4	...	7.8
	Roll-on	av.	13.4	66.7	...	12.5
	Cold	31.8	6.7[b]	39.5	...	7.0
	Roll-on	25.7	5.7	54.0	...	6.7
	Cold	28.3	5.4	51.7	...	5.6
	Roll-on	24.1	6.5[b]	51.8	...	7.2
	Cold	24.5	5.7	45.7	...	6.3
	Roll-on	19.5	7.2[b]	74.9	...	9.6
	Cold	24.5	6.3[b]	48.4	...	6.7
	Roll-on	19.3	6.7	62.4	...	8.1
	Cold	av. [24.7]	6.0	46.3	...	6.4
	Roll-on	av.	6.5	60.8	...	7.9

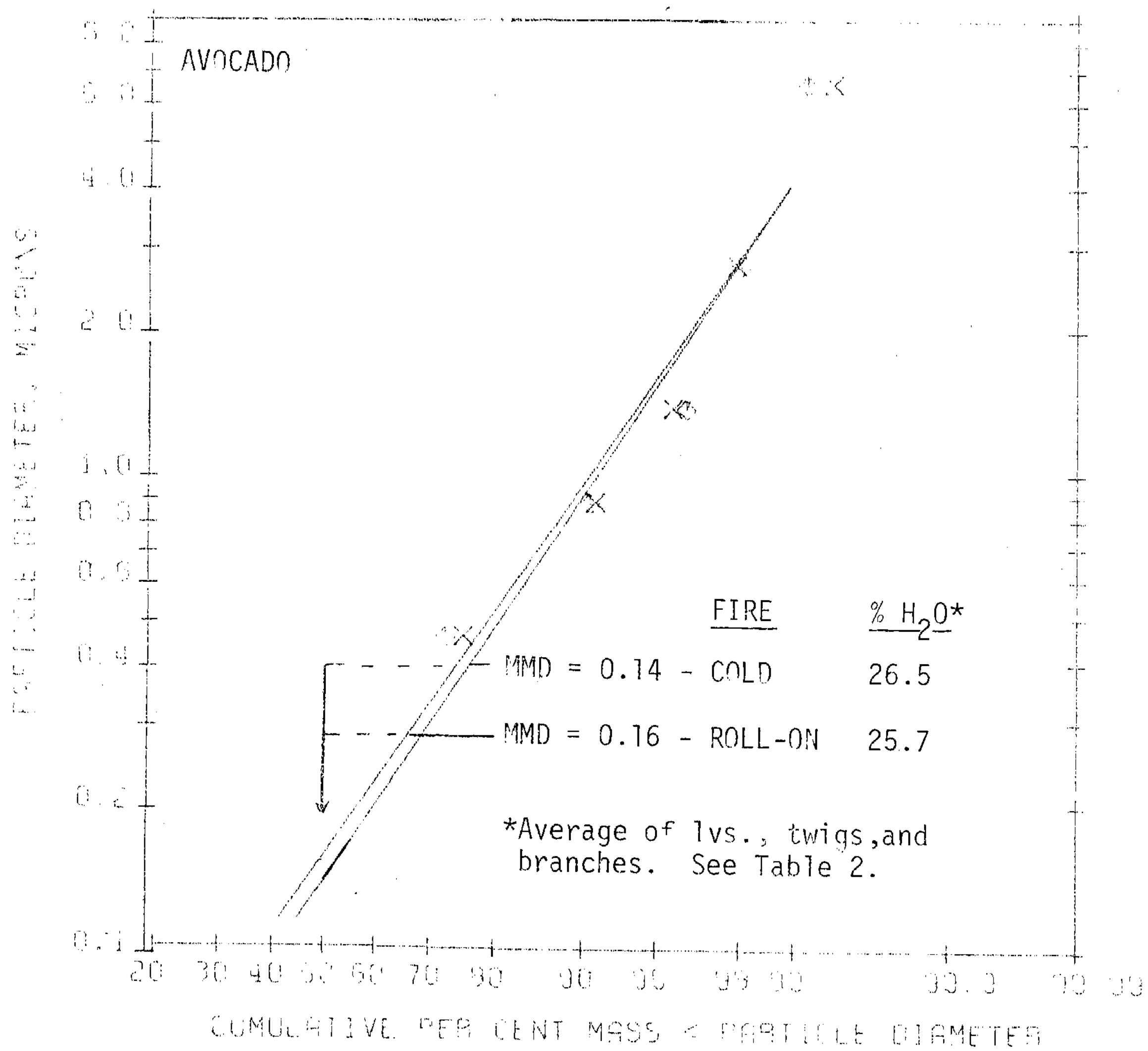

APPLE
FIRE
% H_2O
MMD = 0.09 - COLD 30.9
MMD = 0.13 - ROLL-ON 34.5
PARTICLE DIAMETER, MICRONS

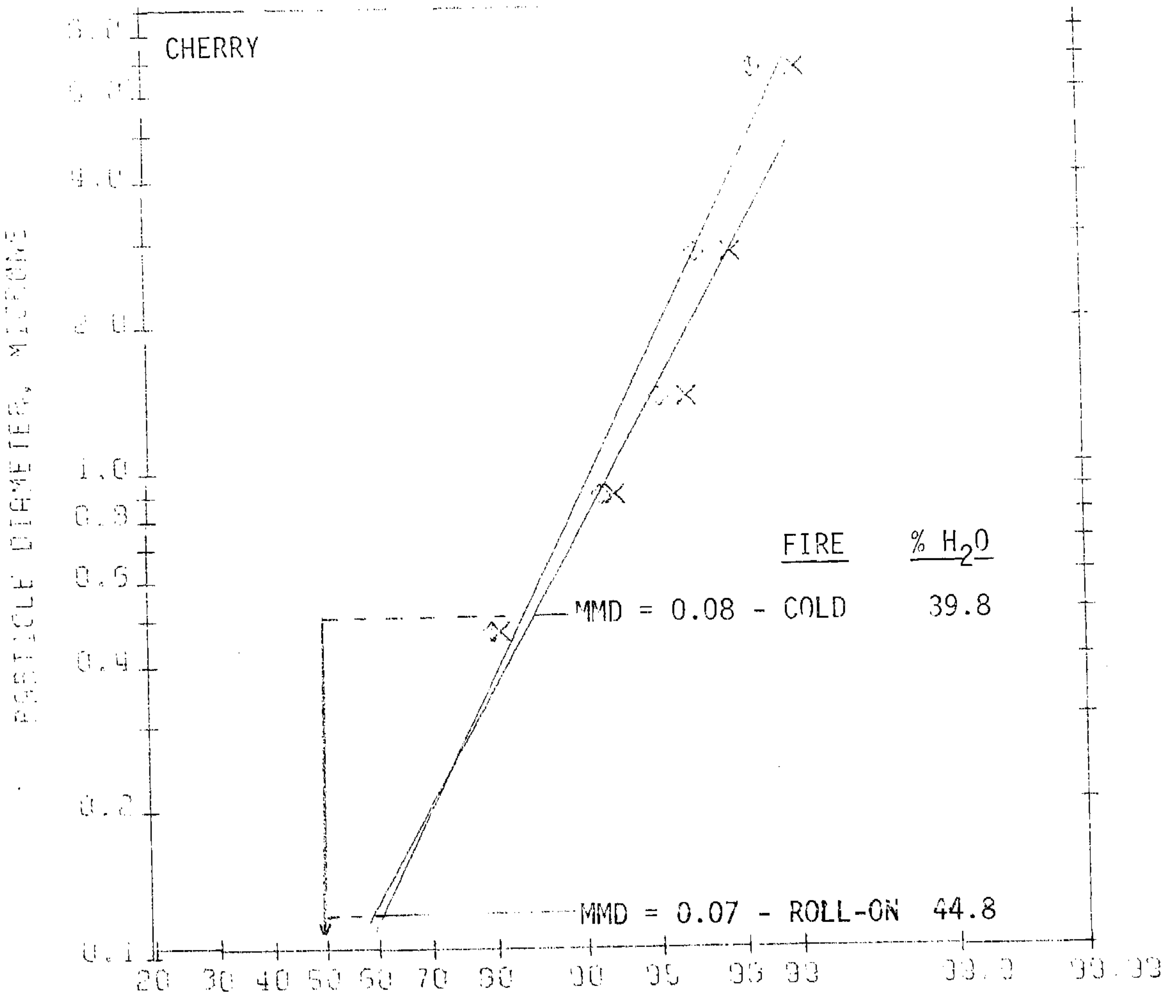

APPLE
FIRE
% H_2O
MMD = 0.05 - COLD 20.7
MMD = 0.10 - ROLL-ON 20.7
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

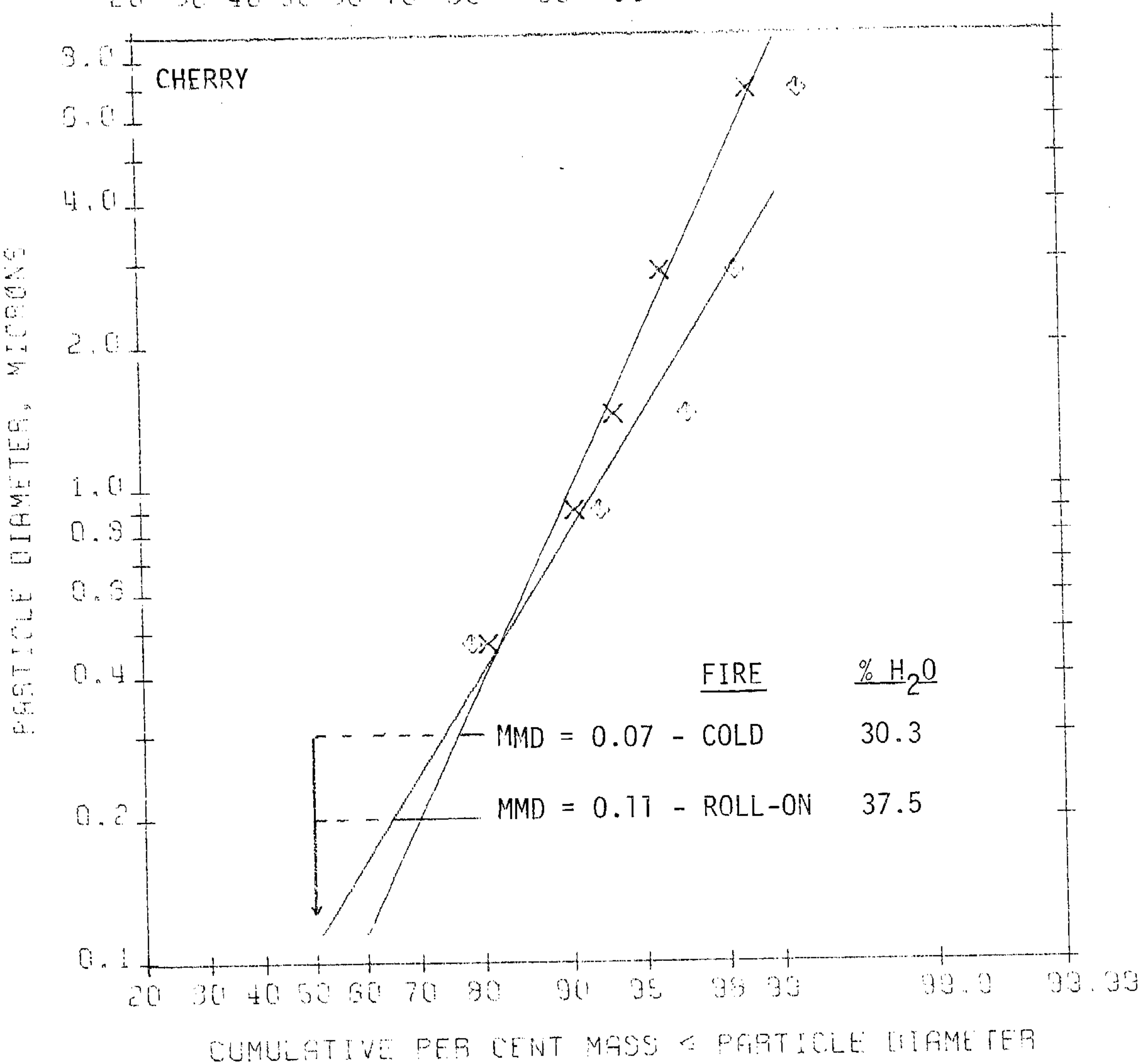

APRICOT
FIRE
% H_2O
MMD = 0.14 - COLD
39.2
MMD = 0.22 - ROLL-ON
41.1
PARTICLE DIAMETER, MICRONS

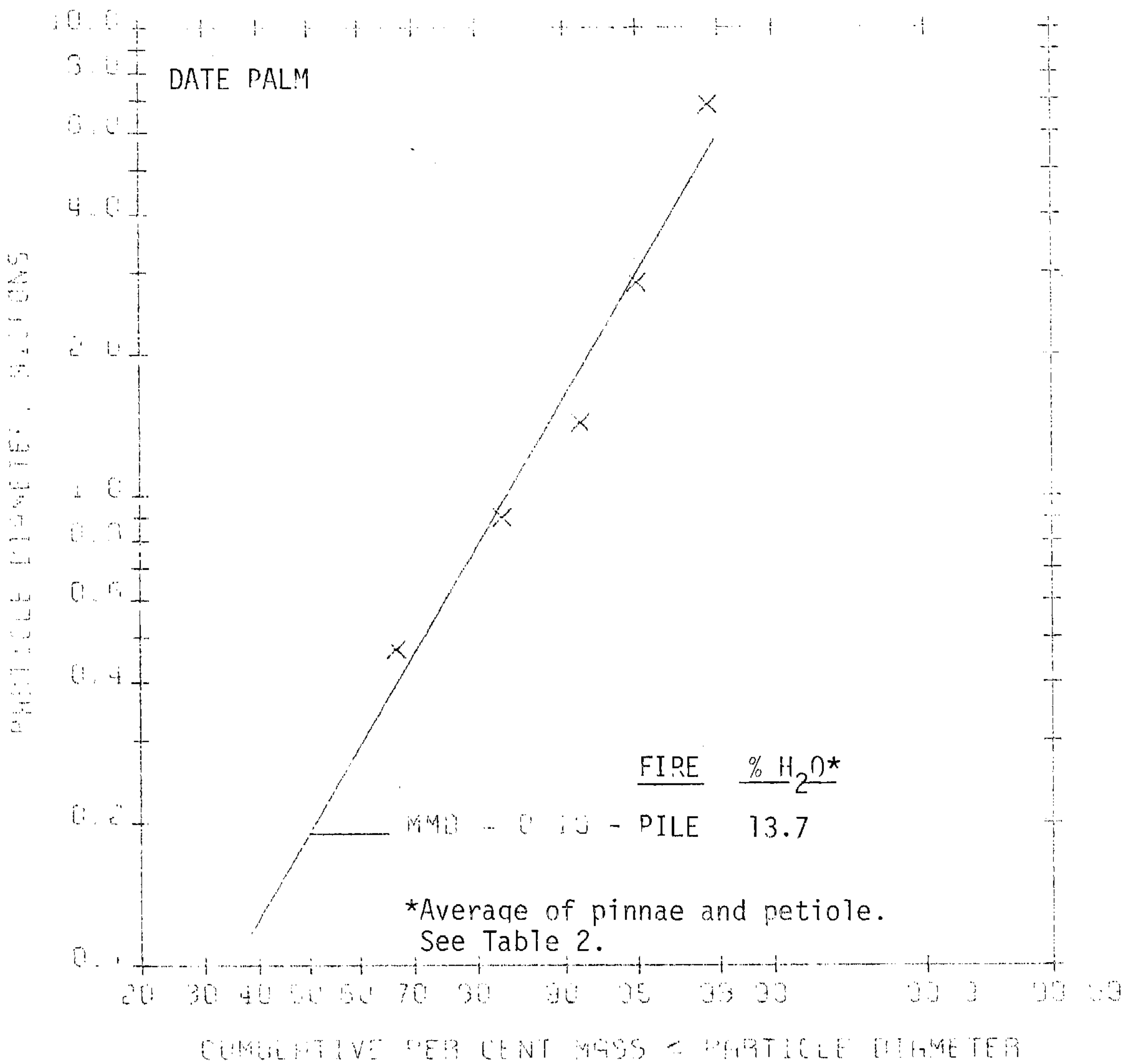

APRICOT
FIRE
% H_2O
MMD = 0.04 - COLD
25.4
MMD = 0.17 - ROLL-ON
28.8
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


AVOCADO
FIRE
% H_2O
MMD = 0.15 - COLD
61.5
MMD = 0.26 - ROLL-ON
57.5


AVOCADO
FIRE
% H_2O*
MMD = 0.14 - COLD
26.5
MMD = 0.16 - ROLL-ON
25.7
*Average of lvs., twigs,and branches. See Table 2.
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


CHERRY
PARTICLE DIAMETER, MICRONS
FIRE
% H_2O
MMD = 0.08 - COLD 39.8
MMD = 0.07 - ROLL-ON 44.8
1.0
0.8
0.6
0.4
0.2
0.1
20 30 40 50 60 70 80 90 95 98 99 99.9 99.99


CHERRY
PARTICLE DIAMETER, MICRONS
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
FIRE
% H_2O
MMD = 0.07 - COLD 30.3
MMD = 0.11 - ROLL-ON 37.5
20 30 40 50 60 70 80 90 95 98 99 99.9 99.99
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


DATE PALM
FIRE % H_2O*
PILE 13.7
*Average of pinnae and petiole.
See Table 2.
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

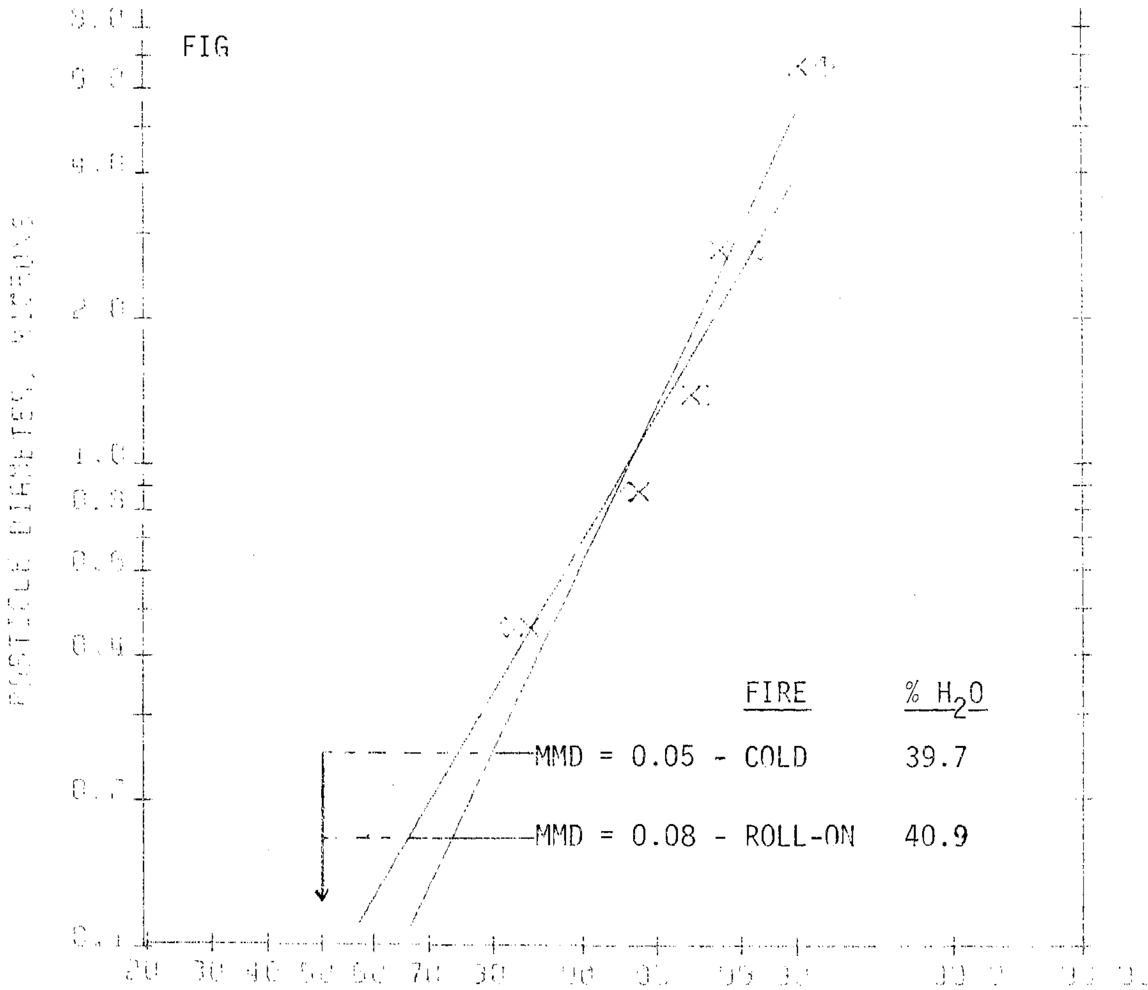


FIG
FIRE
% H_2O
MMD = 0.05 - COLD
39.7
MMD = 0.08 - ROLL-ON
40.9
PARTICLE DIAMETER, MICRONS

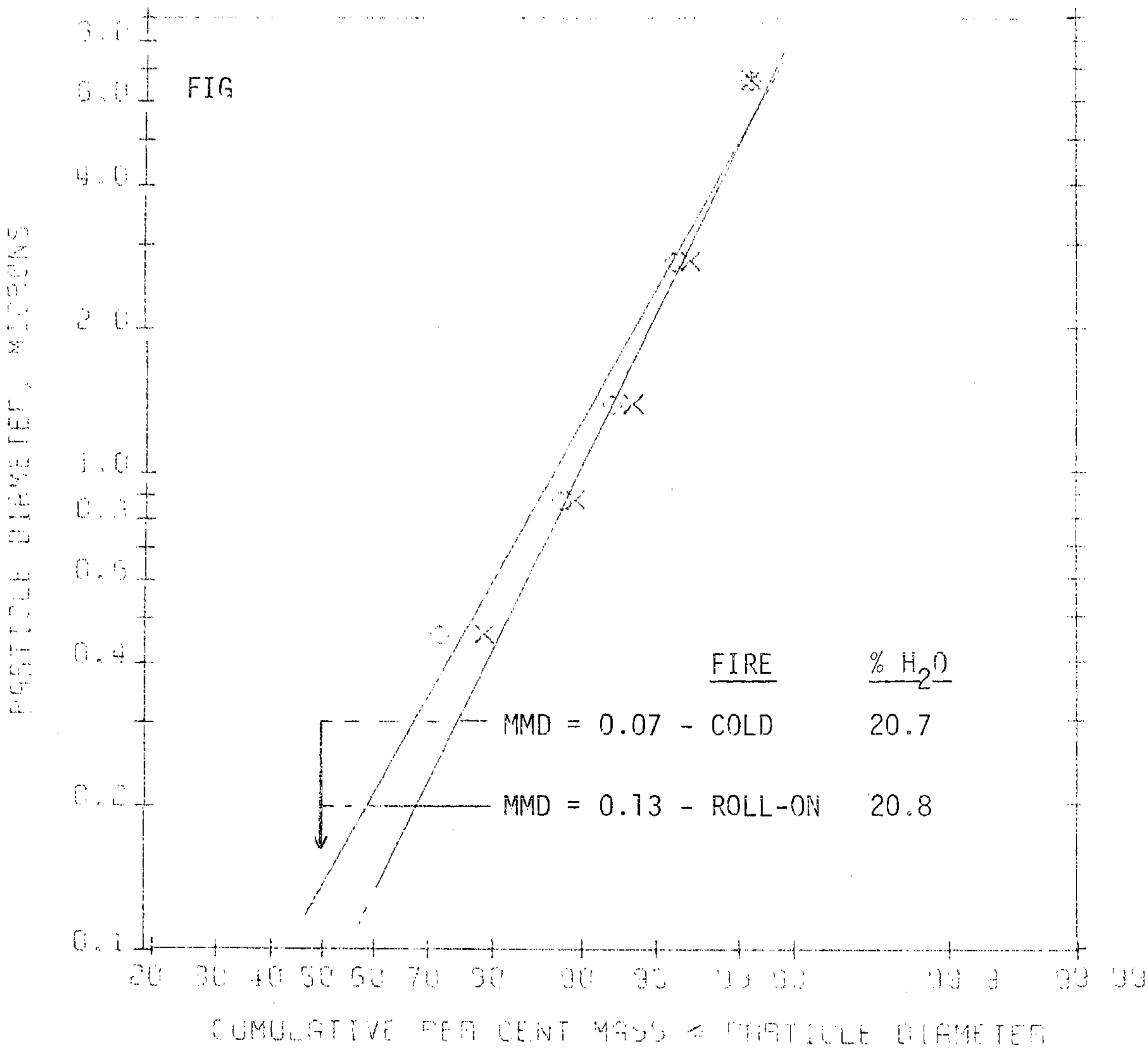
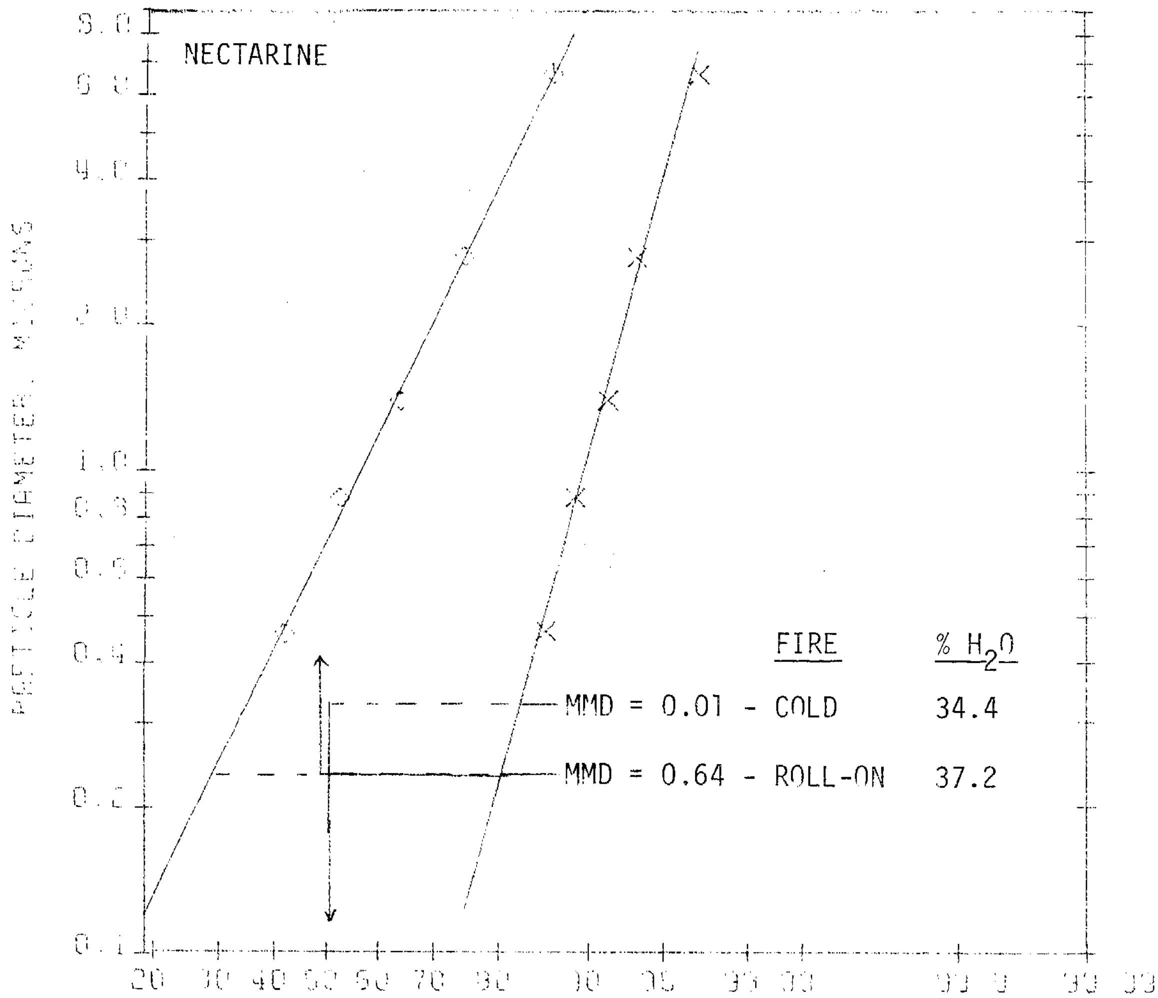
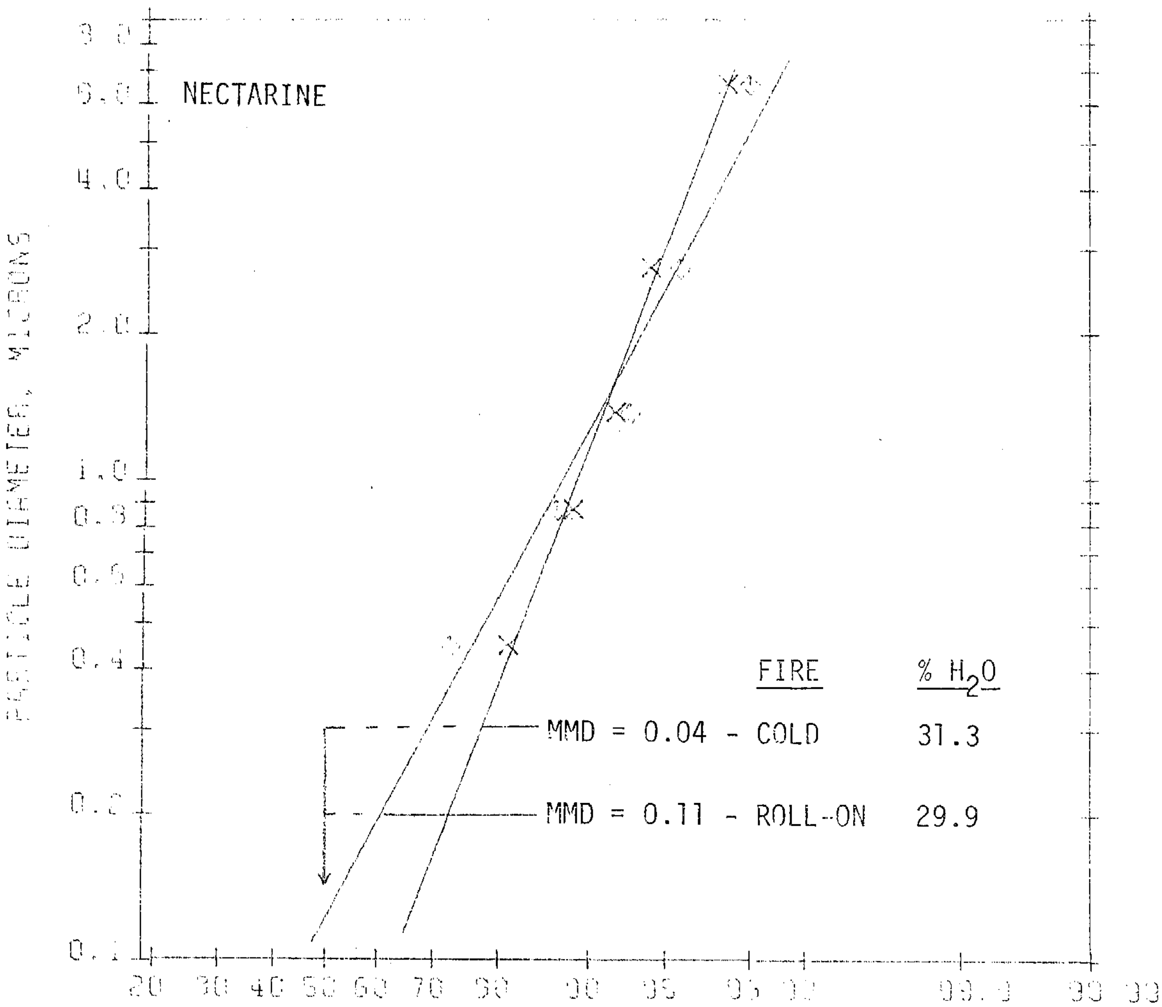
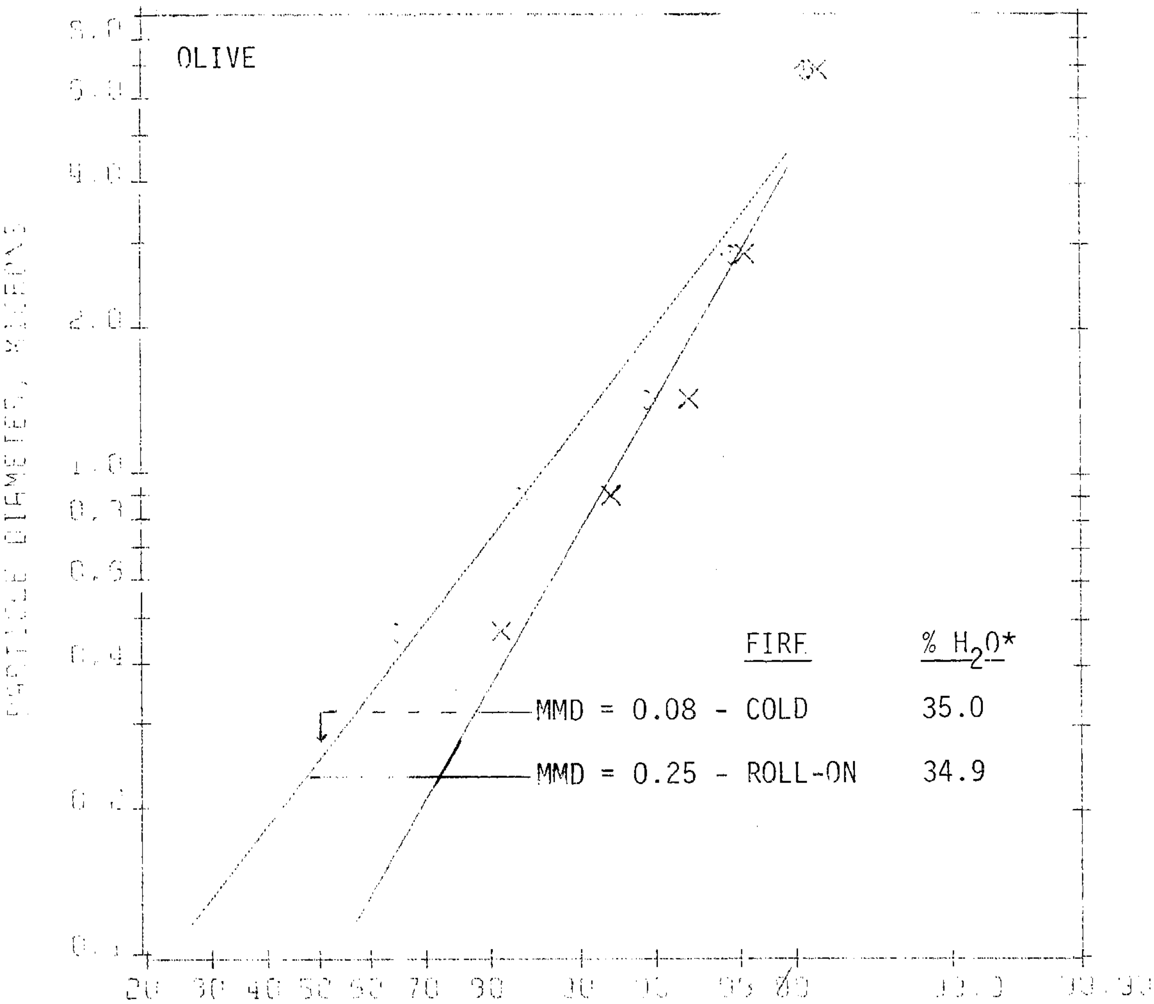
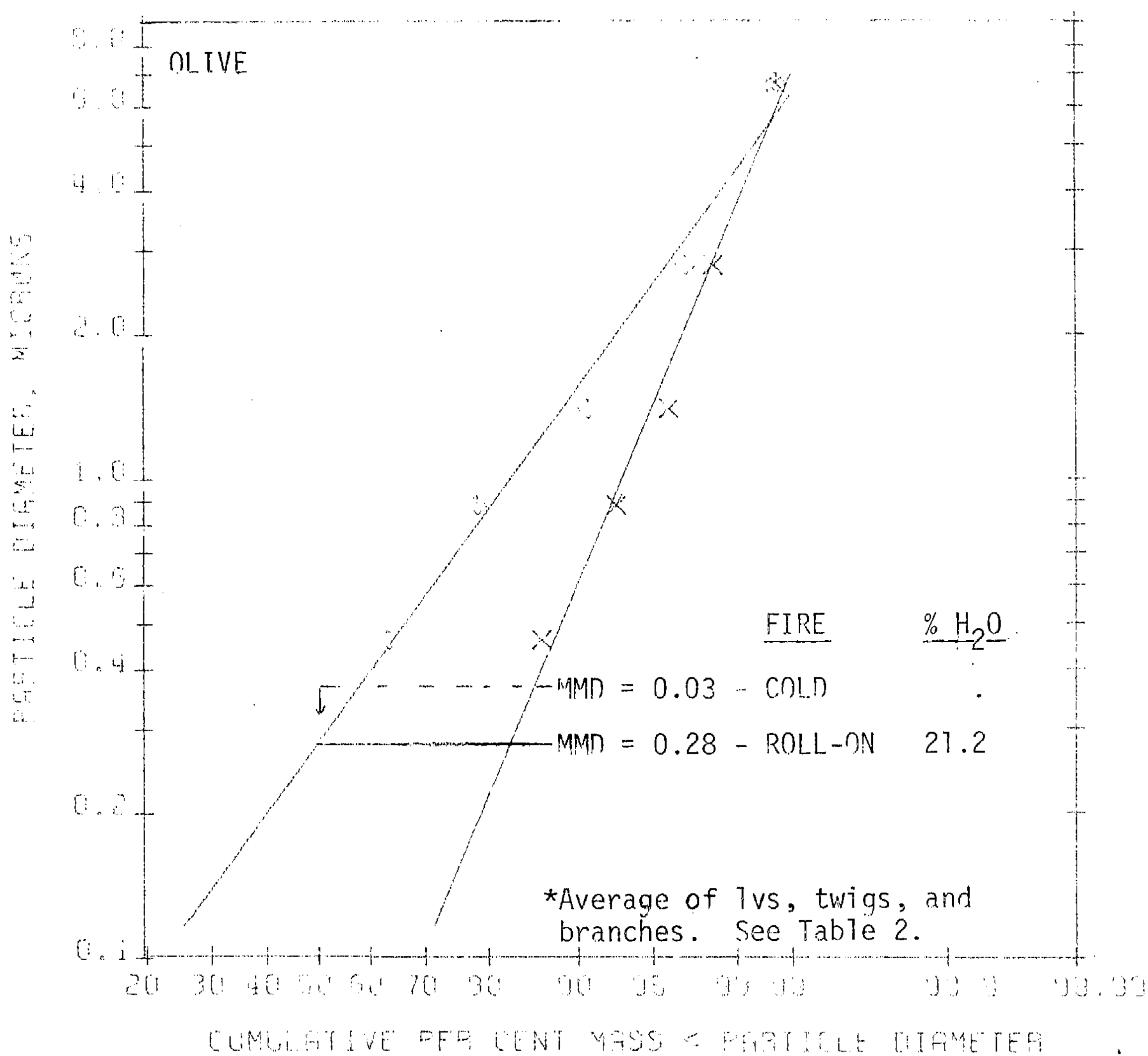


FIG
FIRE
% H_2O
MMD = 0.07 - COLD
20.7
MMD = 0.13 - ROLL-ON
20.8
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

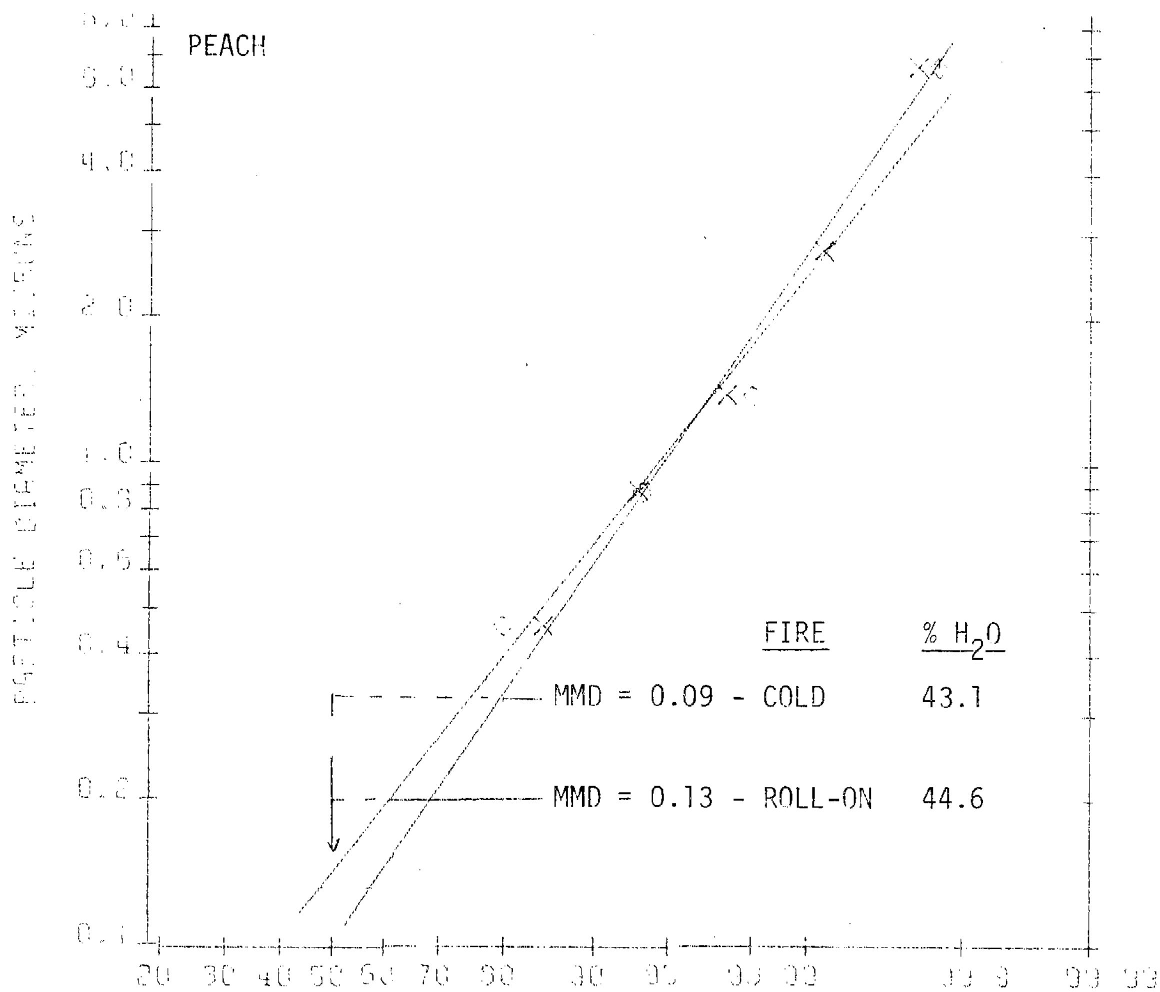

NECTARINE
PARTICLE DIAMETER, MICRONS
FIRE
% H_2O
MMD = 0.01 - COLD 34.4
MMD = 0.64 - ROLL-ON 37.2

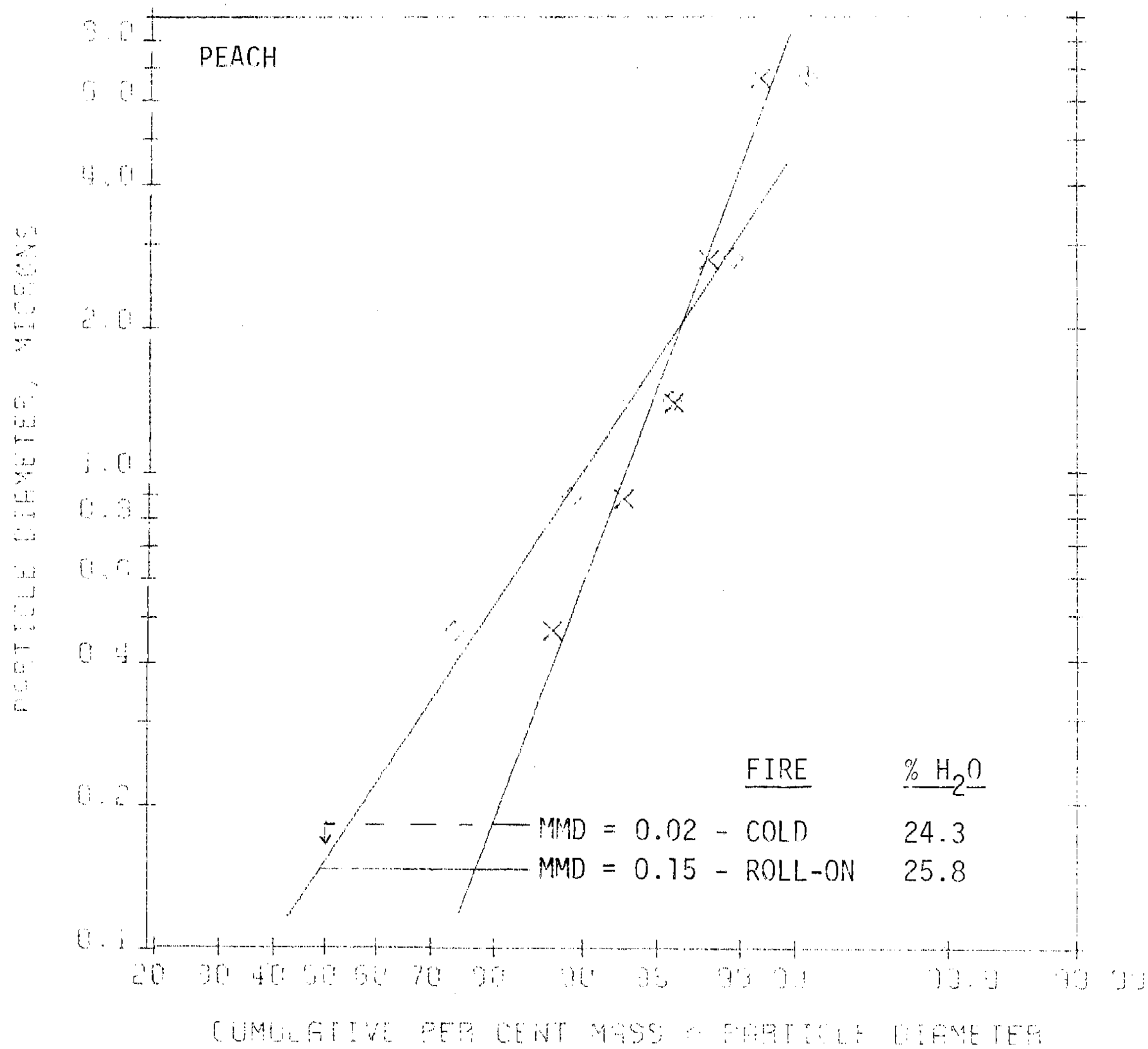

NECTARINE
PARTICLE DIAMETER, MICRONS
FIRE
% H_2O
MMD = 0.04 - COLD 31.3
MMD = 0.11 - ROLL-ON 29.9
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

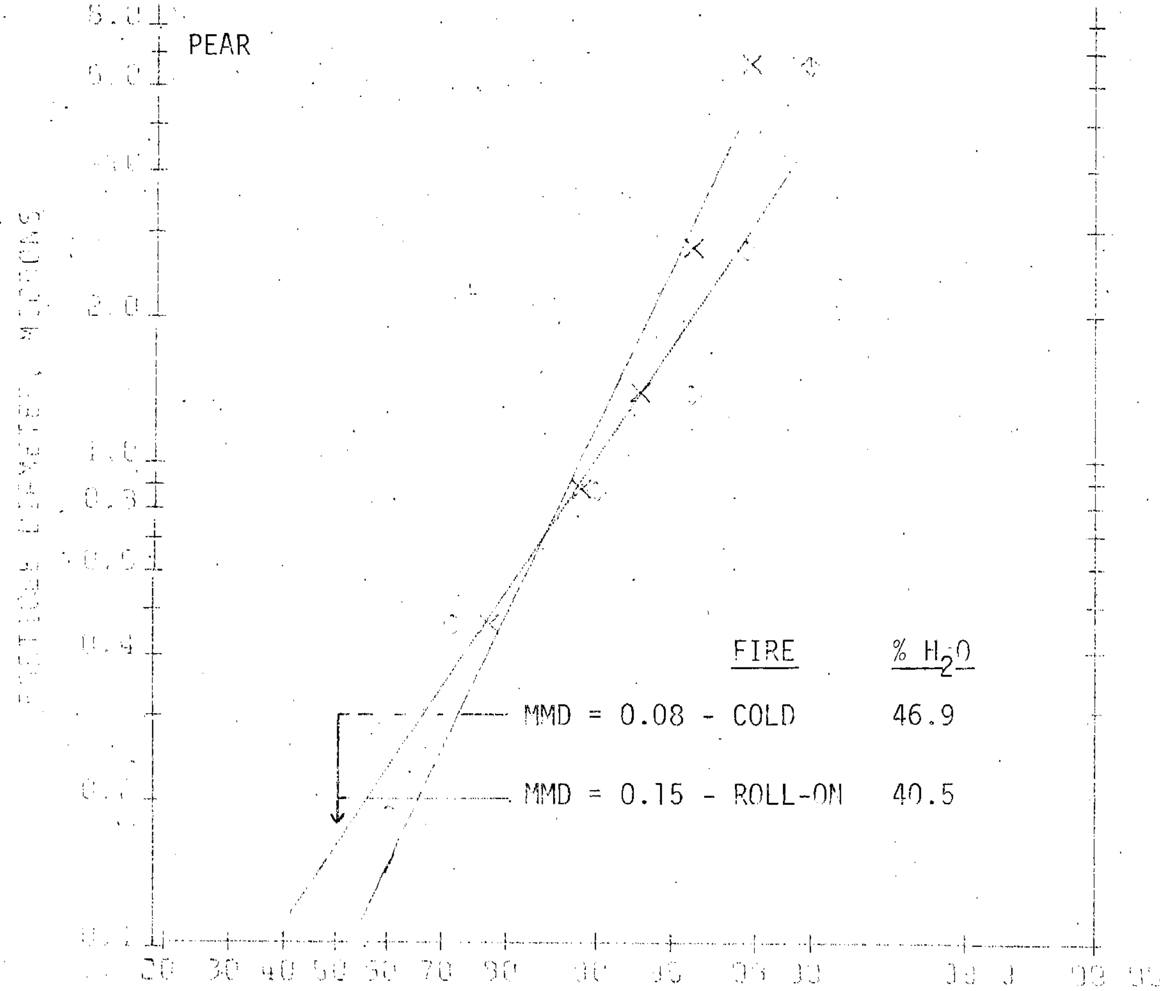


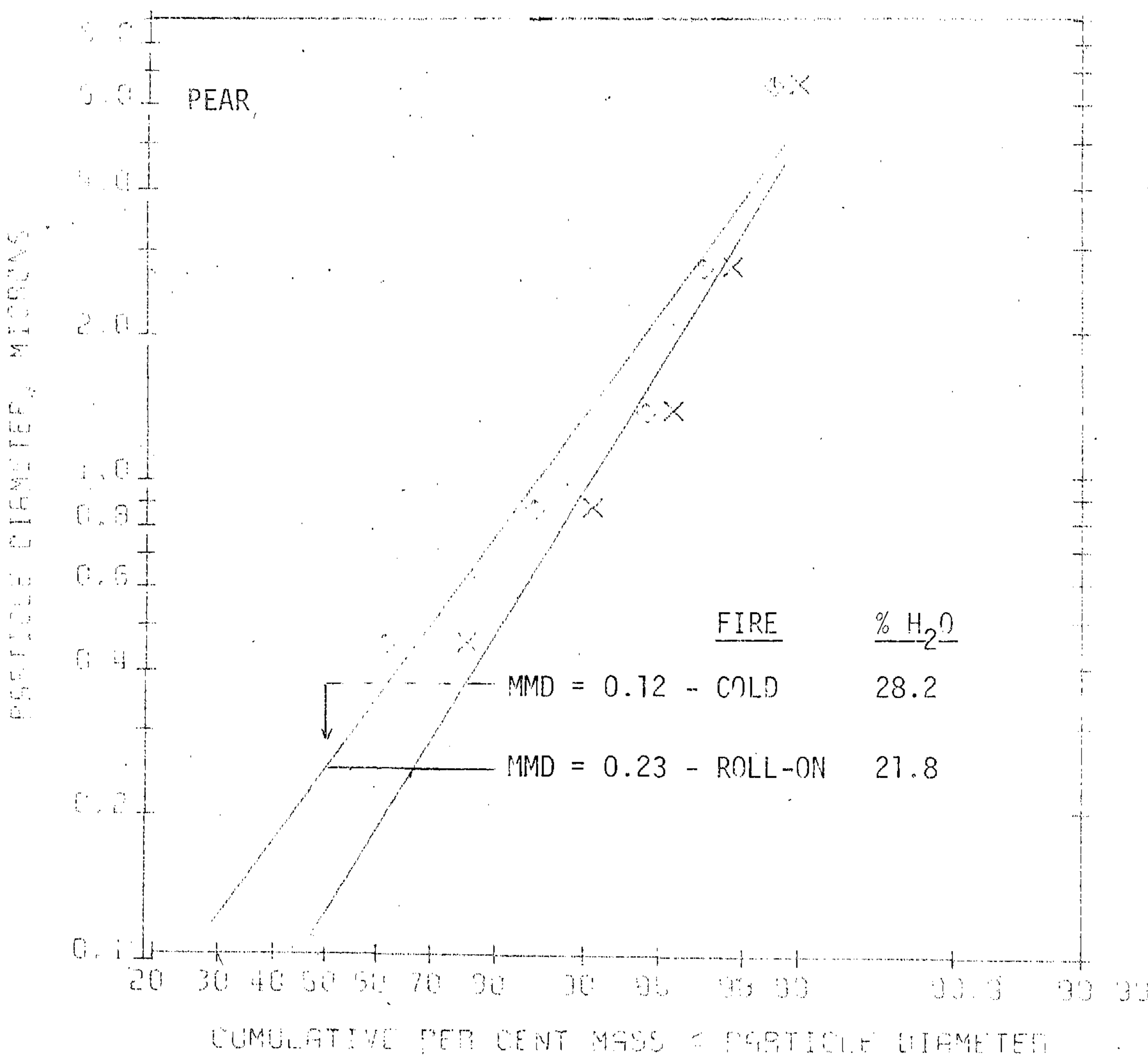


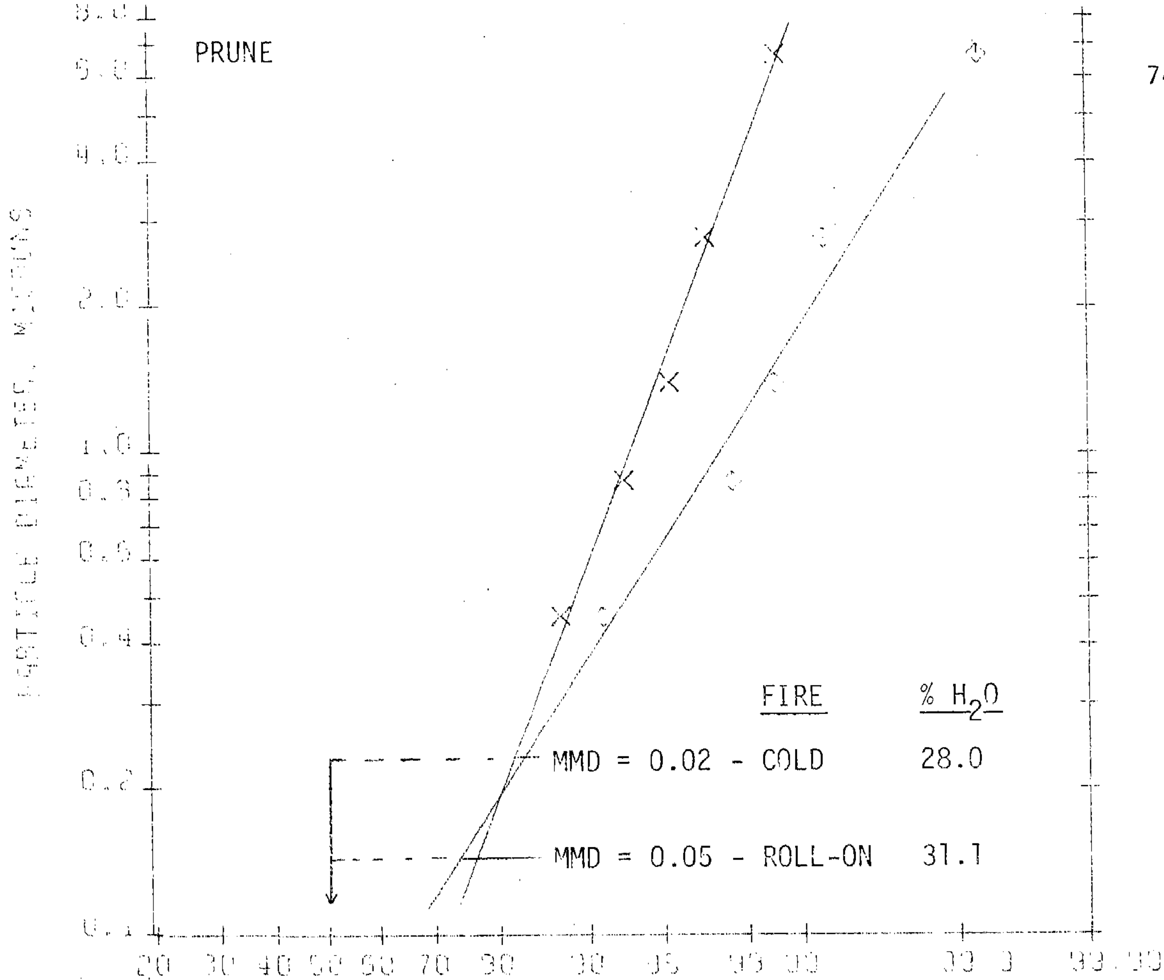
*Average of lvs, twigs, and branches. See Table 2.

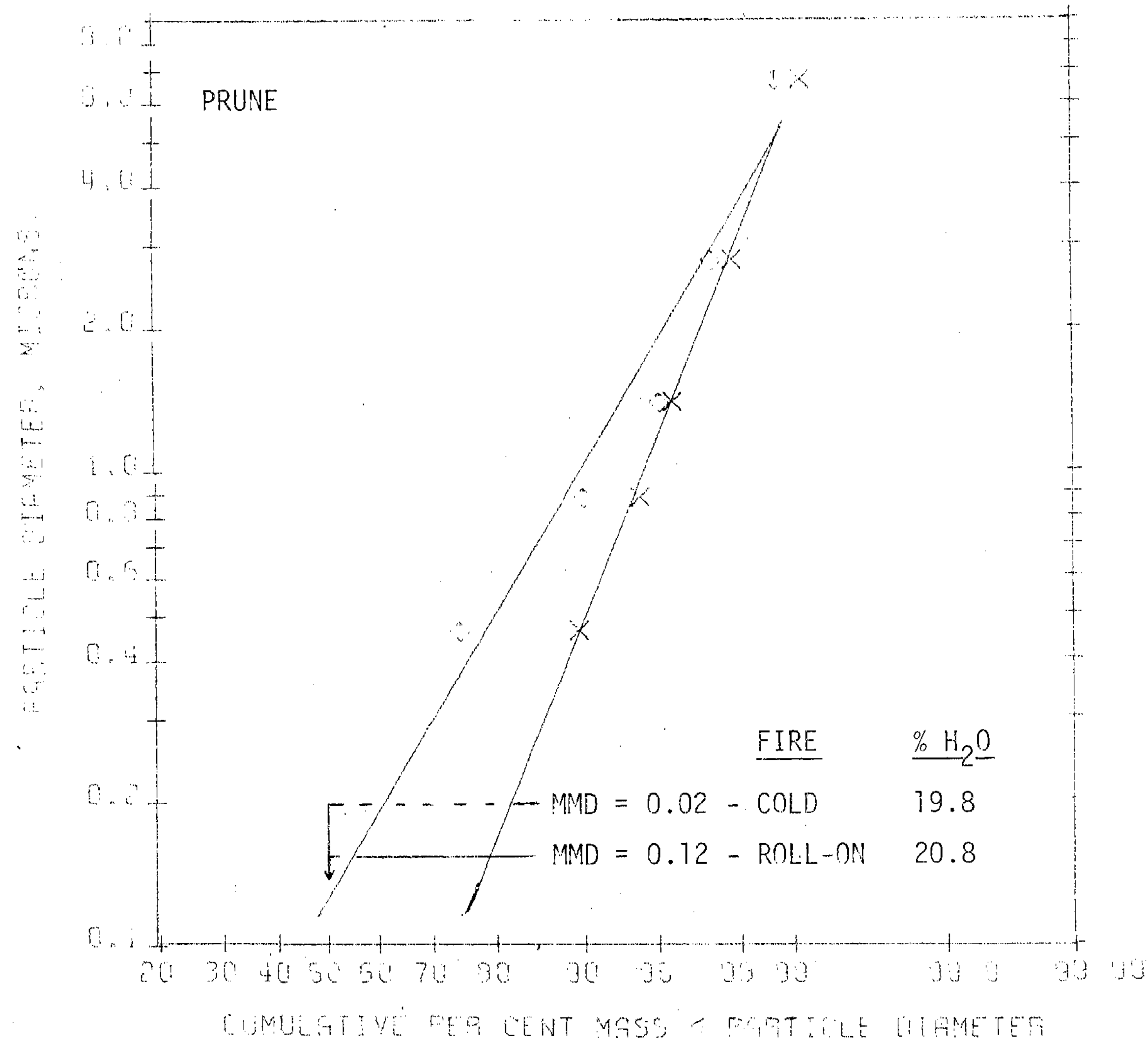

PEACH
FIRE
% H_2O
MMD = 0.09 - COLD
43.1
MMD = 0.13 - ROLL-ON
44.6

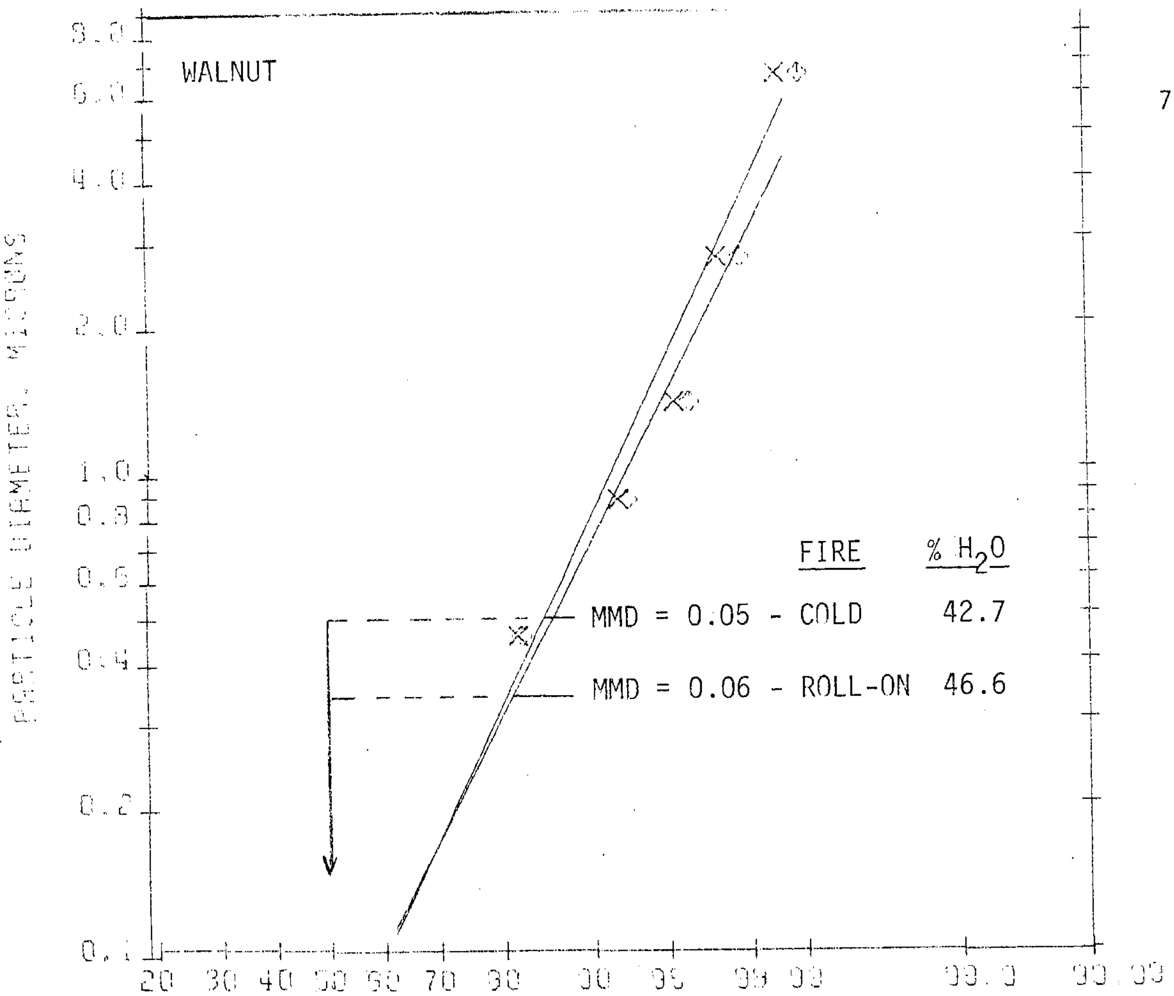

PEACH
FIRE
% H_2O
MMD = 0.02 - COLD
24.3
MMD = 0.15 - ROLL-ON
25.8

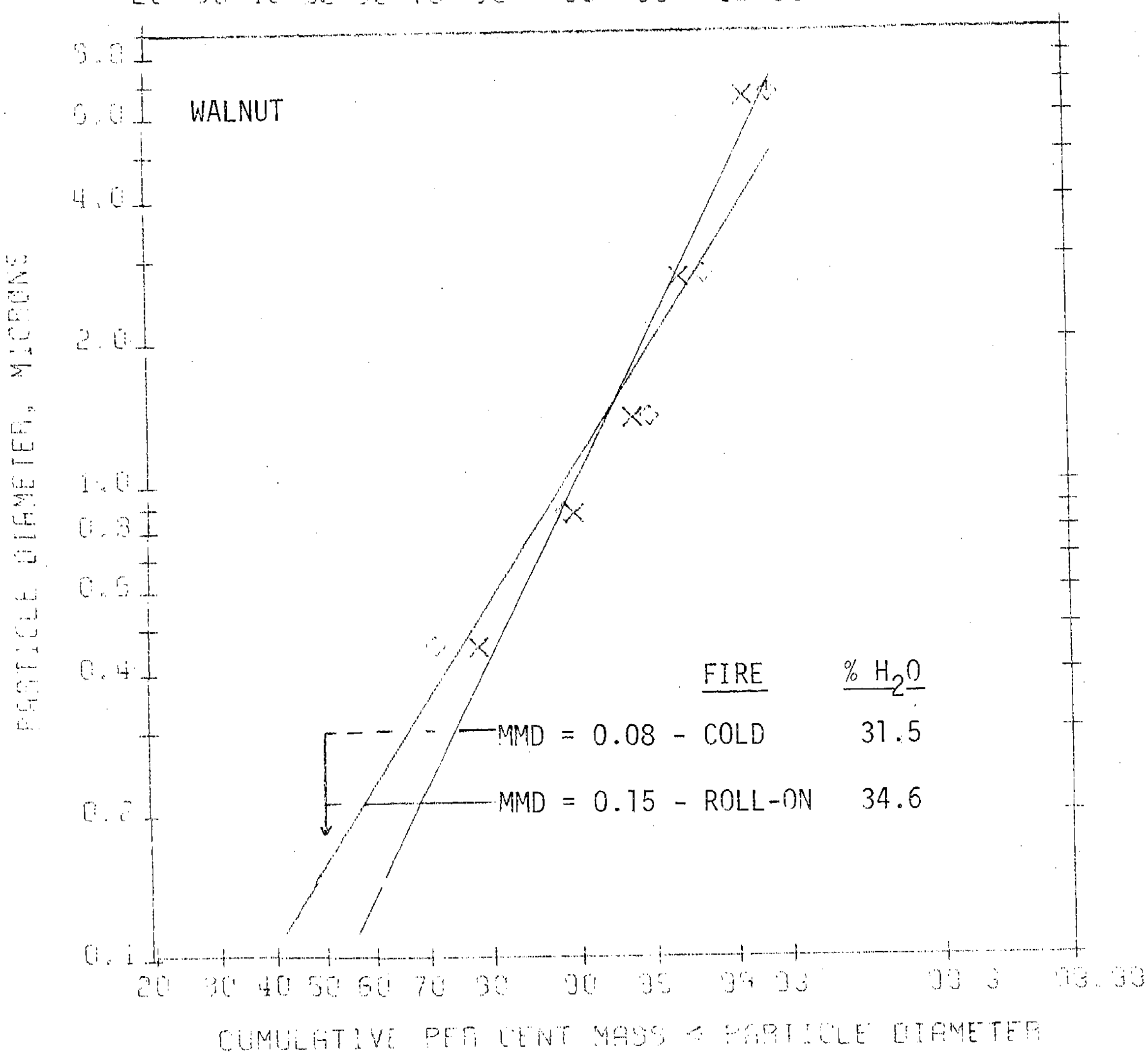

PEAR
FIRE
% H_2O
MMD = 0.08 - COLD
46.9
MMD = 0.15 - ROLL-ON
40.5
20 30 40 50 60 70 80 90 95 98 99 99.8 99.99

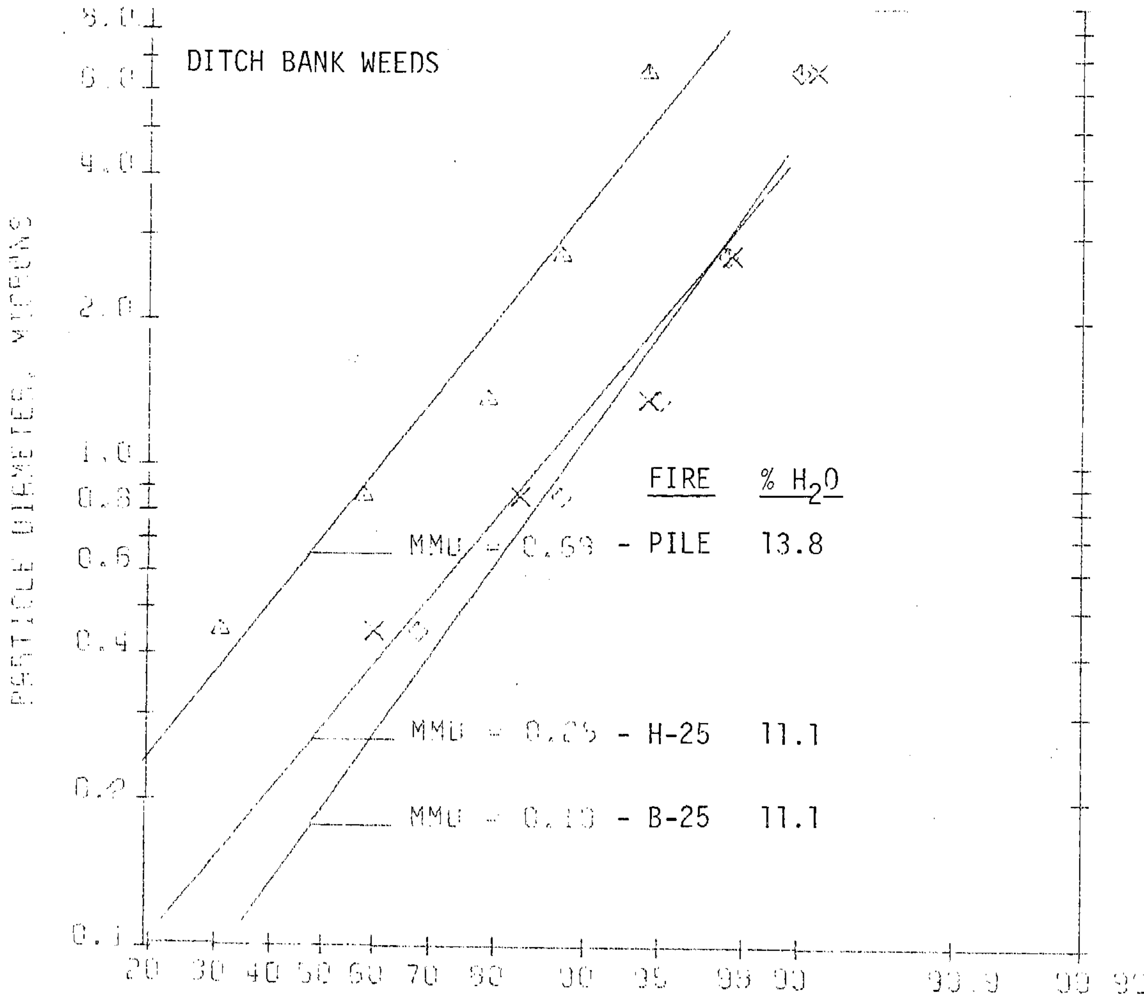

PEAR
FIRE
% H_2O
MMD = 0.12 - COLD
28.2
MMD = 0.23 - ROLL-ON
21.8
0.1
20 30 40 50 60 70 80 90 95 98 99 99.8 99.99
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

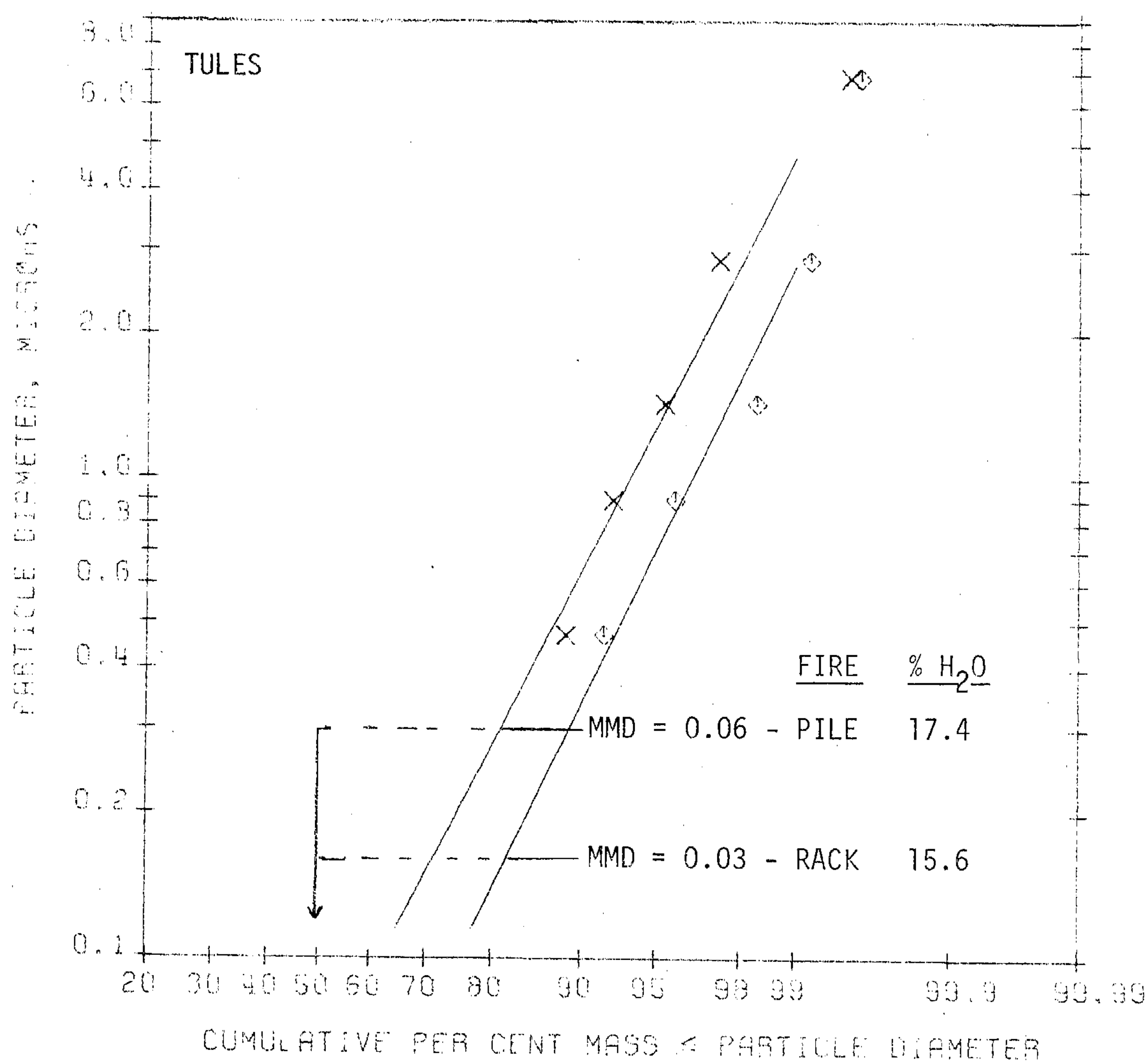

PRUNE
FIRE
% H_2O
MMD = 0.02 - COLD
28.0
MMD = 0.05 - ROLL-ON
31.1


PRUNE
PARTICLE DIAMETER, MICRONS
FIRE
% H_2O
MMD = 0.02 - COLD
19.8
MMD = 0.12 - ROLL-ON
20.8
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


WALNUT
FIRE
% H_2O
MMD = 0.05 - COLD 42.7
MMD = 0.06 - ROLL-ON 46.6
PARTICLE DIAMETER, MICRONS


WALNUT
FIRE
% H_2O
MMD = 0.08 - COLD 31.5
MMD = 0.15 - ROLL-ON 34.6
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER


DITCH BANK WEEDS
FIRE % H_2O
MMD = 0.69 - PILE 13.8
MMD = 0.25 - H-25 11.1
MMD = 0.10 - B-25 11.1
PARTICLE DIAMETER, MICRONS


TULES
FIRE % H_2O
MMD = 0.06 - PILE 17.4
MMD = 0.03 - RACK 15.6
PARTICLE DIAMETER, MICRONS
CUMULATIVE PER CENT MASS < PARTICLE DIAMETER

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2. Darley, E. F., G. E. Miller, Jr., J. R. Goss, and H. H. Biswell. Air pollution from forest and agricultural burning. Final Report, Calif. Air Resources Board Project 2-017-1, 86 pages, 1974.

3. Darley, E. F., S. Lerman, G. E. Miller, Jr., and J. F. Thompson. Laboratory testing for gaseous and particulate pollutants from forest and agricultural fuels. In, "Air Quality and Smoke from Urban and Forest Fuels--International Symposium," National Academy of Sciences, pp. 78-89 (1976).

4. Marple, V. A. A fundamental study of inertial impactors. Ph.D. Thesis, Mechanical Eng. Dept., Univ. of Minnesota, December, 1970.